SUMMARY TECHNICAL REPORT OF DIVISION 17, NDRC

VOLUME 1

DETECTION OF LAND MINES AND SOUND RANGING

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 17
GEORGE R. HARRISON, CHIEF

WASHINGTON, D. C., 1946

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SUMMARY TECHNICAL REPORT

OF THE

NATIONAL DEFENSE RESEARCH COMMITTEE

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members.

These were:

Division A—Armor and Ordnance
Division B—Bombs, Fuels, Gases, & Chemical Problems
Division C—Communication and Transportation
Division D—Detection, Controls, and Instruments
Division E—Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1—Ballistic Research
Division 2—Effects of Impact and Explosion
Division 3—Rocket Ordnance
Division 4—Ordnance Accessories
Division 5—New Missiles
Division 6—Sub-Surface Warfare
Division 7—Fire Control
Division 8—Explosives
Division 9—Chemistry
Division 10—Absorbents and Aerosols
Division 11—Chemical Engineering
Division 12—Transportation
Division 13—Electrical Communication
Division 14—Radar
Division 15—Radio Coordination
Division 16—Optics and Camouflage
Division 17—Physics
Division 18—War Metallurgy
Division 19—Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

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NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them, and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

The research work of Division 17 included a wide variety of projects, ranging from the detection of land mines to the characteristics of the human ear, from helium purity indicators to the telemetering of strain gauges, from odographs to sound-ranging devices. It is a tribute to the broad knowledge of the Division Chiefs—Paul Klopsteg and, later, George R. Harrison—and to the versatility of the men who worked under them that so diverse a program was handled so competently.

A considerable portion of the work of Division 17 had to do with the shattering noise of modern war, and answers were sought and supplied to such questions as: How much noise can a human being stand? What clues must the human ear have in order to understand a spoken message? How much distortion can be tolerated? These and other phases of the Division's work are dealt with in the Summary Technical Report prepared under the direction of the Division Chief and authorized by him for publication.

The diversity of the Division's projects made it inevitable that its staff should be composed of men with many types of scientific training and that the Division should draw on contractors with a wide range of experience and skills. The studies of noise, in particular, meant that the technical staff must include physicists, acousticians, and psychologists. For the ability and devotion of these men of many aptitudes we express our gratitude.

VANNEVAR BUSH, Director
Office of Scientific Research and Development

J. B. CONANT, Chairman
National Defense Research Committee

FOREWORD

THE APPLIED PHYSICS DIVISION of the Office of Scientific Research and Development [OSRD] was organized late in 1942 under the chairmanship of Dr. Paul E. Klopsteg, who was responsible for the work of the Division until shortly before the completion of its work when other duties required his full attention. Most of the projects which had been initiated by the Instruments Section of the National Defense Research Committee [NDRC] during 1940 and 1941 and which were not concerned with optics were turned over to the Applied Physics Division on its inauguration. Dr. Klopsteg as Chief and Dr. E. A. Eckhardt as Deputy Chief went with them from the Instruments Section to the new Division.

The Summary Technical Report which is presented in these volumes thus covers the accomplishments of projects set up by both Section D-3 and Division 17. The work of the Division covered a very wide range of fields. The term *Applied Physics* served in lieu of a more descriptive name for a Division which was in fact the one to which was assigned any scientific problem which did not properly come under one of the other divisions of NDRC.

Actually the Division was an association of three Sections having rather dissimilar responsibilities and fields of activity. In setting up these Sections it was necessary to group the projects already under way into a small number of coherent categories, and those chosen were Sound, Electricity, and General Instrumentation. The work of the Division consisted entirely of the integrated efforts of these three Sections, whose membership will be found listed on a succeeding page.

For more detailed reports on the technical work of the Division than are contained herewith the detailed contractors' reports of Division 17 should be consulted, and appropriate reference to these have been made throughout the present volumes. The results obtained are also presented in less technical form in that volume of the history of OSRD entitled *Optics and Applied Physics in World War II.*

GEORGE R. HARRISON
Chief, Division 17

PREFACE

THE RESEARCH AND DEVELOPMENT program of Division 17, NDRC, was concerned with those problems in physics not specifically covered in other divisions of NDRC. As the result, the Division fell heir to a myriad of miscellaneous problems of a physical nature which, in themselves, were not often interrelated. It would have been exceedingly difficult, if not impossible, for Division 17 to set up a sufficient number of sections to deal specifically with all the various classes of problems which fell under its jurisdiction. Therefore, the projects of the Division were assigned to one of three sections —Section 17.1, Instruments; Section 17.2, Electrical Equipment; and Section 17.3, Acoustics— whose broad titles permitted a general, even if somewhat loose, classification. It was not always easy to decide, at times, under which of these three broad categories a given project should be placed. In such cases, considerations such as immediate convenience and availability of experienced personnel were often the determining factors.

The Summary Technical Report describing the activities of Division 17 is presented in four volumes. In an attempt to achieve a little greater uniformity of subject matter, the projects were organized within the various volumes without regard to their section classification. Consequently, there is, on the whole, little relationship between volume and section number. Because of the varied problems dealt with in the Division's program, very little continuity is to be found from chapter to chapter in any volume. Each chapter attempts to summarize independently the results of a particular project.

Since there were a large number of diversified projects in Division 17, it was obviously impossible to do justice to each, even in summary. It is not intended that the importance of any project described herein should be judged by the amount of page space allotted to it. Naturally, certain problems involved more research and development than others before they could be brought to a successful conclusion. In many cases, this is reflected in the Summary Technical Report. On the other hand, the presentation of the projects may mirror the enthusiasm (or lack of it) of the individual author at the time of writing. Therefore, the reader who desires more than a broad panorama of the Division's activities is referred to the Microfilm Index for more complete details.

An attempt has been made in this first volume of the Division 17 Summary Technical Report to group together the projects dealing with the development of detecting devices for various purposes and methods of detection of certain objects. Not all the projects within the Division that conceivably could be classified under these two categories are included. In general, only those detecting devices or methods which were developed for specialized or unique purposes found their way into this volume.

The first three chapters of this volume discuss a related group of projects while the remainder present the results of unrelated researches. An effort has been made to see that each chapter presents the problem clearly, outlines the methods of attack, and states the important results or conclusions. Every reasonable effort has been made to keep this volume free from error, scientific or otherwise. Should some creep in, the authors and editor would be grateful to have them called to their attention. Although this is a technical report, by its very nature it is inevitable that occasionally opinions other than scientific are expressed. These do not necessarily reflect the opinions of the authors, editor, or NDRC as a whole, but rather those of Division 17.

It should be borne in mind that the material contained in these chapters represents a summary of the combined efforts of many men who labored so faithfully for so long for so little personal recognition. Although certain of these men, as authors, bore the brunt of preparing this volume, many others contributed freely of their time to read the authors' manuscripts to check for accuracy, Division and NDRC policy, to offer invaluable suggestions and criticisms, and to answer innumerable questions. To these men, then, as well as to the authors, the editor of this volume expresses his deep appreciation.

Lest the mention by name of all those who contributed to the preparation of this volume be considered as a listing in a minor hall of fame, it has been purposely avoided. The name of the author will be found under the chapter titles. Where no name appears, the editor, with the help of innumerable Division members, Contractor employees, and friends, has prepared the summary from the various contractors' reports.

CHAS. E. WARING
Editor

CONTENTS

Chapter 1

DETECTION OF LAND MINES

1.1 INTRODUCTION

1.1.1 Purpose of Report

THIS REPORT is designed to summarize for a technically trained reader the scientific program conducted by Section 17.1 and its predecessor, Section D-3, of the National Defense Research Committee [NDRC], for the development of land mine detectors. It is to be submitted, along with the other summary technical reports of this series, to the Army and Navy in fulfillment of final obligations of NDRC.

1.1.2 Organization and Scope

It is intended that this report will present sufficient background to enable the reader to understand why and how the various problems were undertaken, and it is intended to present a clear picture of the "state of the art" at the termination of the work. Emphasis is given to the two detectors, one to locate metals and the other nonmetals, which were placed in large-scale production, as well as to the final experimental models nearing production which represented the highest development state at the close of World War II. No attempt is made to include material sufficient to enable other investigators in this subject to continue the experimental program without resort to bibliographical reference material. An attempt has been made, however, to record the developments in such detail that the next investigators will understand why certain attacks on the problems involved were rejected.

The report is organized in five major sections. The introduction is intended primarily to orient the reader and to present a brief overall picture of the development program: its results, its evaluation, and the problems it left unsolved. The next three sections each deal with a general class of mine detectors. The breakdown of all detectors into these three classes is admittedly arbitrary and open to reasonable objections; for example, many detectors do not fit uniquely into a single classification. It was under the classifications adopted for this report, however, that the work was organized throughout the course of the program. The fifth section deals with the problems which were current at the close of World War II, such as possible countermeasures and anti-countermeasures. Here, too, the implications of the trend in mine warfare are considered in terms of a future peacetime research program.

1.1.3 Army Interest and Liaison

In the Army Service Forces [ASF] the responsibility for the development of mine detection equipment was delegated to the Chief of Engineers, and the responsibility for equipment production to the Chief Signal Officer. In the chain of command, the engineering responsibility fell to the Minefields and Fortifications Branch, Research and Development Division, Office, Chief of Engineers, which delegated the primary development responsibility to the Engineer Board, Fort Belvoir, Virginia, and its Applied Electronics Branch. Intimate liaison was maintained with these and other officers by Section 17.1, and earlier by Section D-3, throughout the course of the development.

1.1.4 Service Projects

The Service control numbers under which the NDRC program functioned were CE-4 and CE-31. CE-4 was accepted by NDRC on February 21, 1941, and was terminated on October 14, 1942. CE-31 was accepted by NDRC in January 1943 and was a continuing project until the end of hostilities.

1.2 SUMMARY

Heavily mechanized and mobile warfare has been generally recognized as an important characteristic of World War II. It was, therefore, natural that certain defensive weapons came to the forefront as a means of limiting

the power and restricting the mobility of the offense. One of the most important of these weapons was the land mine. The strategy and tactics involved in the employment of land mines, including their use as a weapon of offense, was highly developed by the German army and, to a lesser extent, by the Italian and the Japanese. Before the United States' entry into the war, the land mine had already emerged as a successful defensive weapon if properly employed, primarily through its use by the Afrika Korps in Libya and Cyrenaica. Thus, one of the earliest problems presented by the Army to NDRC was the development of a portable detector of land mines suitable for operation by foot soldiers.

The development of equipment for the passage of enemy minefields can be arbitrarily broken down into three groups: mine detection, mechanical clearance, and demolition clearance. Of these, mine detection is the most important as it was used much more extensively than any other type of equipment in combat warfare for the penetration of enemy minefields. While mine detection and removal were originally designated a function of combat engineer troops, the prolific use of anti-tank and anti-personnel mines by the enemy made it impossible for this assignment to be carried out in practice. The technique of mine detection and removal thus became, of necessity, familiar to most ranks and organizations within the Army.

1.2.1 Military Requirements

Military requirements for mine detectors changed during the war as the enemy introduced new mines and new techniques in planting, and also as the battleground progressed from Africa to Italy, to the European theater of operations [ETO], and similarly in the Pacific. The initial Service request, designated Service project or directive CE-4, called for the development by Section D-3, NDRC, of two metal detectors—one capable of detecting nonferrous metals and the other capable of detecting mines containing ferromagnetic parts. Specifically, they were required to detect a ½-lb metallic object at a depth of 24 in. With the development of detector set SCR-625 through the combined efforts of NDRC and the Engineer Board, primary attention was directed by NDRC to fulfill the requirements of CE-31, calling for the development of a detector capable of locating explosives as such buried in the ground and nonmetallic anti-tank mines. With the introduction of the Schu mine[a] and other anti-personnel mines containing very little metal, military requirements changed to include the location of small nonmetallic mines and of extremely small amounts of metal, such as are used in fuzes and igniters, at considerably reduced depths of burial. The encountering of lava soil of high magnetic susceptibility in Italy and of other soils with magnetic characteristics in northern Europe and the Pacific theaters required that our mine detectors operate over such soils without producing spurious signals which would mask the mine signals. It was also recognized early that mine detectors must be able to operate over ground heavily littered with shrapnel and other battle refuse.

Practically, military requirements for mine detectors were expressed in terms of the detection of known, widely used enemy mines at operational depths of burial under a wide variety of soil conditions. Anti-personnel mines, such as the Schu mine, the Mustard Pot mine, and the S mine, were rarely encountered at depths greater than 2 in. Most were found on top of the surface (camouflaged) or with less than ½ in. of earth covering them. Anti-tank mines (such as the German Tellermine series, Riegel mines, and Topf mines) were usually buried not more than 6 or 8 in. below the ground, although there were many instances of anti-tank mines being buried to depths as great as 3 ft. In the Japanese theaters such enemy anti-tank mines as the Yardstick mine, the Type 3 Flowerpot, and the J-93 were rarely buried even 6 in. deep. The Japanese anti-personnel mines were usually above, flush with, or just below the surface.

The above requirements had to be fulfilled under battle conditions, involving detection at night, frequently under direct enemy fire.[47]

[a] For information concerning this and other mines that will be mentioned, see STR, Division 2, Volume 1, or Engineer Intelligence bulletins.

An additional important consideration is that mine locating with a detector must be faster, safer, and at least as reliable as mine locating by probing methods. Probing, the locating of mines by prodding the ground (usually in a direction about 45 degrees with the vertical), is a tedious procedure—slow, yet quite reliable and safe if done by an expert. The method was widely employed throughout the war. Its effectiveness was the major reason for discarding a number of mine detector developments.

1.2.2 Detector Developments

Two detectors, developed with the cooperation of NDRC, were placed in large-scale production and issued to combat troops. The first of these was a metal locator designated by the Signal Corps the SCR-625, and the second, a so-called nonmetal detector, was designated detector set AN/PRS-1. At the close of World War II the development of a universal detector (that is, one combining the desirable features of the SCR-625 and AN/PRS-1) was nearing the production stage. The Signal Corps' identification for this instrument was the AN/PRS-6.

Detector Set SCR-625

The SCR-625, developed under an NDRC contract with the Hazeltine Service Corporation, Little Neck, L. I., comprised, essentially, a modified Hughes bridge operating at a frequency of 1,000 c. The bridge coil assembly consisted of three concentric, coplanar coils of different diameters arranged so that the mutual inductance between the inner and outer coils and the middle coil was very nearly zero. The outer and inner coils were connected to an audio oscillator, and the middle coil was connected to an amplifier, the output of which was fed into a meter and a parallel resonator. When the bridge was balanced the coefficient of coupling between the oscillator coils and the detector coil was zero, and no signal was heard in the earphones. The introduction of metal into the a-c field produced by the oscillator coils disturbed the field and thus altered the zero coupling condition. The resulting signal was amplified and detected, indicating the presence of a mine in the field of the detector. Altogether 115,000 SCR-625 detectors were procured by ASF. The total cost of this procurement program was very close to $25,000,000. The experimental development cost was about $150,000.

Detector Set AN/PRS-1

The AN/PRS-1, an original development by the RCA-Victor Division, Indianapolis, Indiana, under a contract with NDRC, is generally listed as a nonmetal detector even though it will frequently detect metallic mines. Its performance in locating metals, however, is inferior to that of a detector like the SCR-625, so that it has been customary to refer to this model as a nonmetal detector. In this locator energy from a 300-mc oscillator is radiated into the ground by means of a simple dipole antenna and reflector system. The operation of the detector is dependent upon the fact that the antenna loading is affected by the presence of surrounding objects, both metallic and nonmetallic. This may be considered as due to a reflection of radiation back to the antenna, or as a variation in the impedance presented to the antenna. The impedance change, in turn, is reflected back into the oscillator, causing a change in loss in the tank circuit of the oscillator. The variation in grid current of the oscillator tube is proportional to the loss in the circuit and can be used as an indication of the change in load. A voltage developed in the grid circuit is used to control an oscillator-amplifier, and variations of the grid current produce aural indications in a resonator. At a cost of about $12,000,000 the Signal Corps procured 29,600 AN/PRS-1 detector sets. Development costs of the AN/PRS-1 within NDRC totaled less than $100,000.

Detector Set AN/PRS-6

The most promising NDRC detector still under development at the close of World War II was the AN/PRS-6, a universal mine detector, also the product of RCA-Victor, Indianapolis. This detector combines a modification of the PRS-1 with a metal detector of the mutual inductance bridge type; it represents merely an engineering advancement in the "state of the art." The nonmetal-detecting portion of this instrument is designed to supplement the metal-detecting portion. It was expected that the

metal-detecting system would, in practice, be sensitive not only to the large anti-tank mines, but also to mines containing extremely small amounts of metal. The nonmetal-detecting portion is sensitive primarily to anti-tank nonmetallic mines, such as the Topf mine and certain variations of the Japanese Type 3 Flowerpot mine. The major weakness of this detector is its inability to detect small anti-personnel nonmetallic mines. Increasing the sensitivity of the nonmetal-detecting portion would increase the possibilities of locating this type of mine, but at the same time would more than linearly increase the number of false indications due to roots, stones, and similar objects. It is believed that a large number of false indications constitute a more serious objection than the lack of sensitivity to anti-personnel nonmetallic mines.

Other detectors developed by NDRC which deserve mention are: (1) the *portable iron detector* [PID], (2) the beach detector, (3) seismic detectors, (4) the *earth current detector* [ECD], and (5) radioactive detectors. Brief descriptions of these instruments follow.

Portable Iron Detector and the AN/PSS-1

The portable iron detector was developed by the Carnegie Institution of Washington, D.C., the NDRC contractor, under project OD-46. The original development called expressly for a device capable of detecting land mines in ferrous cases and suitable for attachment to a vehicle. The PID is, in effect, an extremely simple magnetic gradiometer or, more exactly, a space-time gradiometer. It consists of two magnetometers aligned with each other, connected with their outputs in opposition. When swept over a ferromagnetic object, one magnetometer, being nearer to the object, will receive a stronger signal than the more remote magnetometer, while the uniform magnetic field of the earth affects both magnetometers equally (if the circuit is properly designed and balanced). Thus detection of ferromagnetic objects is achieved without aligning the measuring devices in any particular direction with reference to the earth's magnetic field. Each magnetometer comprises a large number of turns of small (No. 40) insulated copper wire wound on a Permalloy rod. The detected signal is amplified and fed into a resonator.

Although this device is light and sensitive, its inability to detect the nonferrous mines used by the enemy is a serious shortcoming. For this reason, the detector was not placed in production. It proved important, however, in furnishing a basis for the development and subsequent small-scale production of the AN/PSS-1, a detector designed for use by swimming members of naval combat demolition teams for the detection of anti-boat mines. The modification of the PID to the AN/PSS-1 was carried out under an Engineer Board contract. The principal modification was the addition of a battery-operated motor, which mechanically rotated the magnetometer coils, making it unnecessary for the operator to sweep the detector continuously in order to pick up a mine signal. A second change was the elimination of the Permalloy rods from the gradiometer; this made it possible to increase the stability of balance and, therefore, the sensitivity. As all known enemy anti-boat mines contained some ferrous metals, the insensitivity of this device to nonferrous metals was not considered a serious objection.

Beach Detector or AN/PRS-5 (XB-2)

The beach detector, a development under NDRC contract by Electro-Mechanical Research Company, Houston, Texas, is a variation of the mutual inductance bridge-type detector which contains certain novel circuit design features. It is operated at a frequency of 465 kc; the use of this frequency enhances the conduction effect as a phenomenon responsible for detection. This accounts for one unusual property: practically 100 per cent detection is obtained for both metallic and nonmetallic mines buried in soils of high conductivity, such as the region on a beach below the high-tide line. Over less-conducting soil the detector's performance approaches very nearly that of the SCR-625 and other standard metallic mine detectors.

Seismic or Electromechanical Type Detectors

Several attempts to use seismic methods to locate nonmetallic mines were made, including the following: (1) measurement of a variation

in the transmission of sonic vibrations between a vibrator and a pickup, each of which is in contact with the ground; (2) reflection of vibrations from a mine due to the discontinuity it presents in the ground to a wave train or pulse propagated in the earth; (3) variation in the resonance properties of the earth over a buried object to acoustic vibrations, as compared to the adjacent earth (i.e., measurement of a variation in mechanical impedance).

Instruments based on the third method proved that detection of both metallic and nonmetallic mines is possible. No acoustic detector was placed in large-scale production, however, because field trials showed two disadvantages: (1) it is dangerous to use because contact must be made with the ground in areas where sensitive anti-personnel mines might be located; (2) the method proved to be slower and less sure than probing. The horizontal cross-sectional area of sensitivity is only about 1 sq ft, and the weight of the detector head is 6 lb or more.

NDRC contractors actively engaged on these developments were the Sun Oil Company Geophysical Laboratories, Beaumont, Texas, and RCA-Victor Division, Indianapolis, Indiana.

Earth Current Detector

A promising detector still under development at the close of World War II was the earth current detector, which was based on the British detector X-7. In this locator a ground loop of wire is laid out and energized by alternating current of frequency 1,000 c and of magnitude from 2 to 50 amp. A detecting-coil system carried by an operator is swept over the ground adjacent to and outside the ground loop. The detector coil is sensitive to anomalies in the a-c field induced by the current loop in the ground. A large area can be swept by the detector for one placement of the ground loop. This, to a certain extent, mitigates the following objections to the device: (1) a large amount of equipment is necessary (trailer-truck with auxiliary power supply) and (2) lack of flexibility in use. Initial experiments with this apparatus showed that it might be sensitive to both metallic and nonmetallic mines. Further experimental work seemed to prove that, for setups practical in the field, nonmetallic mines could not be detected using audio-frequency excitation. Detection of metallic mines appeared to be feasible at rather large depths of burial, particularly in the case of ferromagnetic objects. A special attribute of this detector arises from the fact that the detector itself has no field associated with it; this permits the detector to locate safely booby-trap mines fuzed with an igniter sensitive to the local field surrounding a detector of the SCR-625 type. The loop-energizing system of the ECD may also be useful for exploding harmlessly mines so fuzed.

Development work on the ECD was carried out for Section 17.1 by the Shell Oil Company Geophysical Laboratories, Houston, Texas.

Radioactivity Methods and "Mamie"

Three other methods investigated for the location of nonmetallic mines were based on radioactivity measurements. In one it was attempted to measure the reduction of the natural radioactivity of the earth (a shielding effect) due to the presence of a buried object which is not itself radioactive. The procedure in this case was to sweep the ground with a sensitive Geiger-Mueller counter. A second method was based on detecting a variation in neutron and γ-ray emissions from the ground when it is bombarded by a neutron source, such as a mixture of a radium salt with beryllium. The third method employed the procedure of measuring γ-ray scattering when the soil is bombarded by γ-rays from a portable source. Detection by these methods, in the main, was demonstrated to be sound in principle but impractical for military use. These investigations were conducted principally by the Texas Company Geophysical Laboratory, Houston, Texas, and the Physics Department, Massachusetts Institute of Technology, Cambridge, Mass.

"Mamie" is the code name for a method of marking friendly mines (usually nonmetallic). Small "buttons" containing radioactive cobalt-60 chloride, a γ-ray emitter, are planted on top of or adjacent to a nonmetallic mine as a part of the standard operating procedure. The marked mines may then be relocated easily by using a sensitive γ-ray detector of the Geiger-Mueller counter type. The Mamie scheme was developed independently by the

Germans and in this country. Before the close of World War II in Europe it was intended to employ American γ-ray detectors for the location of marked German Topf mines. The Physics Department, MIT, was responsible for this research under NDRC contract.

1.2.3 Countermeasures and Anti-Countermeasures

Electric influence fuzes for land mines, actuated by metallic detectors, have been developed both in this country and in Germany. Such a fuze was actually employed by the Germans against Russian mine detectors. It consisted of a few turns of wire, in the form of a coil, and a sensitive relay. Current induced in the coil by the magnetic field of a metallic detector of the SCR-625 type operated the relay, which in turn actuated an electric detonator. This device has been duplicated by the Signal Corps, and another influence fuze, of the proximity fuze type, was developed earlier by Section T, NDRC. A contractor of the Engineer Board has designed a metallic detector circuit which nullifies the effectiveness of the German-type fuze. This is accomplished by reducing the field strength put out by the field coil as the detector approaches a mine (i.e., the mine signal automatically reduces the current flowing in the field coil). The advantages of the ECD for combating this countermeasure have already been mentioned.

Other types of countermeasures to mine detectors have been developed (e.g., the tilt igniter), and there is every reason to believe that more will be produced in the future. The entire field, including the design of both countermeasures and anti-countermeasures, has not yet been completely surveyed.

1.2.4 Evaluation

The SCR-625 detector set proved to be a successful and useful instrument in combat. It was employed by the U. S. Army throughout World War II, though it was obsolescent in the later stages. For example, it was necessary to make expedient field modifications in certain instances, enabling the detector to operate over soils of appreciable magnetic permeability. The ending of hostilities precluded the replacement of the SCR-625 by a better detector of the same type, known as the AN/PRS-3. It is now believed that as a result of the early NDRC work on metallic mine detectors and, perhaps more important, later Engineer Board contracts, the problem of metallic mine detection has been solved rather completely, and the techniques involved in the design have been worked out satisfactorily. This statement applies particularly to locators of the mutual inductance type utilizing circuits which discriminate against reactive signals caused by magnetic permeability of the ground. Designs have also been completed, under Army contracts, which include limited anti-countermeasure features without serious loss in sensitivity.

Engineering design of special-purpose detectors (e.g., the beach detector and the PID) have not been brought to the same state of advancement. This can be accounted for by a lack of interest on the part of the using Services. While there is much to be said for the Service point of view, it can be argued logically and with considerable weight that modern warfare is most complex, requiring, in many instances, special-purpose equipment to perform certain tasks efficiently and safely.

The entire field of countermeasures and anti-countermeasures involving metallic mine locators is relatively new and unexplored. Vigorous investigations on this subject resulting in new techniques may change present concepts of metallic mine detector design radically. This field should not be neglected in formulating a peacetime research and development program.

In evaluating the metallic mine detection program during and prior to World War II, one serious deficiency may be mentioned. While the SCR-625 was in its initial production stage (spring 1942), the phase discrimination principle for improving its performance was understood and reduced to practice. But the importance of this principle was not realized until some time later; by then it had been rediscovered independently by a contractor of the Engineer Board. The time loss could not be retrieved, with the consequence that no replacement for the SCR-625 was issued to combat troops.

In the two and a half years after the completion of the first prototype model of the AN/PRS-1, no major developments were made which can be said to have greatly improved the performance of nonmetallic and universal mine detectors. Engineering changes, however, were quite marked: the weight of the equipment was materially reduced, sensitivity was increased slightly, and spurious indications due to inadequate height compensation were largely removed. The U-H-F detectors last developed were still unable to detect reliably small nonmetallic mines with a major dimension less than four inches, and in certain soil conditions they could not reliably detect large anti-tank mines. Although these soil conditions occur only occasionally, they are still sufficiently frequent to destroy confidence in the detectors. The detectors are also plagued by false indications due to roots, stones, clumps of grass, weeds, and other conditions which are all too characteristic of practically any field on which a detector would be operated. It may be said fairly that not only is the problem of detection of nonmetallic mines inadequately solved, but also that no satisfactory solution had been obtained at the close of World War II. It seems clear that the problem will exist as long as armies fight on land or occupy enemy-held territory. It is concluded, therefore, that one of the important responsibilities of a peacetime research program is to carry on research and development toward the discovery of an adequate nonmetallic mine detector. The primary need is for a novel method of approach to the problem, since investigations based on methods described in this report have reached the point of seriously diminishing returns. Stated another way, this problem requires the basic research approach rather than engineering modifications of principles and methods employed heretofore.

1.3 METALLIC MINE DETECTION

The problem of the development of a metallic mine detector was first presented informally to NDRC by the Corps of Engineers in the fall of 1940, and subsequently as project CE-4. At the time most of the nations at war had already developed and were using portable mine-locating equipment. It was unfortunate that little or no information concerning these instruments, even about those developed by Britain and France, was available in this country. Thus, many widely varying approaches to the problem were considered.

1.3.1 Possible Detection Principles

Listed below are a number of the possibilities which early were discussed by the Hazeltine Service Corporation, the original NDRC contractor, as a basis for the design of a metallic mine locator.

Distortion of Earth's Field

Earth Inductor Gradiometer. Detection would be effected by detecting the distortion in the earth's magnetic field in the vicinity of a magnetic body, utilizing two astatic rotating coils.

Variation of A-C Permeability by Distortion of Earth's Field. Distortion of the earth's magnetic field would be detected by astatic coils on cores of Permalloy, Perminvar, or other special magnetic materials, magnetized differently by the net field present at the individual coils.

Variation of Self-Inductance of a Single Coil

This method would be applicable to any metallic body, not just a ferromagnetic one. The sensitivity would vary approximately with the inverse sixth power of the distance from the object.

Variation of Balance of Inductance Bridge. When one of two coils of an inductance bridge is nearer the object than the other, the balance is disturbed. This method could be used at audio or radio frequencies.

Beat-Frequency Method. Detection would be based on the variations of a frequency of oscillation, as controlled by the self-inductance of a single coil, by means of a beat note between the frequency of the search-coil circuit and a fixed frequency.

Variation of Mutual Inductance

Devices in this class employ separate units for transmitter and receiver. Both audio and radio frequencies are applicable.

Audio-Frequency Device. A coil arrangement would be made such that zero coupling results between the sending and receiving coils in homogeneous space. The coupling change is detected and amplified directly.

Radio-Frequency Device. This would be similar in principle to the audio-frequency device with the additional possibility of using a modulated carrier.

Beat-Frequency Method. It was proposed to control the frequency of a beat oscillator by the mutual inductance between the sending and receiving coils.

Reflection of Short Waves

All the methods outlined above depend on the disturbance of a magnetic field in the vicinity of a metallic body. The distortion of the earth's field is applicable only to magnetic bodies. The field associated with sending and receiving coils is entirely an induction field since the distance involved is only a small fraction of a wavelength. At frequencies so high that the radiation field becomes important at close range, there is a possibility of detection by means of the reflection of short waves.

1.3.2 Military Characteristics

Some of the early military characteristics and specifications for a metallic mine detector may be listed as follows.

1. When a concentrated mass of not more than ½ lb of either steel, brass, or bronze, in the form of a cylinder, is buried in the earth at a depth of 2 ft, and the detecting element is moved in a horizontal plane 1 ft above the ground surface, the device shall detect and locate the mass accurately.

2. The location of the mass is to be indicated unmistakably both by a movement of a visual indicator and by an increase in the amplitude of the tone from a sonic resonator. The signal shall be a maximum when the locator is held vertically over the object.

3. The device shall be capable of the above performance in all types of soil, whether wet or dry, and also when the metallic object is submerged in 2 ft of either fresh or salt water.

4. The operation of the device shall not be affected by a soldier's normal equipment, e.g., steel helmet, rifle, or bayonet.

5. The device shall not interfere with radio reception, and its operation shall not be affected by radio transmission.

6. The entire equipment shall be compact and capable of withstanding rough usage.

7. The device shall be of suitable weight and construction for transportation and operation by one man.

8. Equipment shall be designed to operate satisfactorily when the height of the detecting element above the ground surface is varied within a range of 4 to 8 in. When the detecting element is moved throughout this range, neither indicator shall give a signal comparable to that caused by a buried mine.

9. The batteries shall have an operational life of not less than 8 hours.

10. The device shall not respond to a large mass of metal, such as a vehicle, which is located with any part thereof placed at a horizontal distance of 4 ft from the center of the detecting element in its operating position.

As World War II progressed, specifications for metallic mine detectors were modified and made detailed, as indicated by the following.

1. Satisfactory detection shall be construed as an increase in rms voltage across the primary of headset HS-30 of 10 db or 40 mv, whichever is greater.

2. At balance, the rms signal across the primary of HS-30 shall be no greater than 40 mv.

3. An 8-in. brass disk, $\frac{1}{16}$ in. thick, shall be satisfactorily detected 18 in. from the detector head.

4. The detector shall locate satisfactorily the presence of a Type 3 Japanese fuze, less pressure spring, 3 in. from the search coil when the fuze body is buried flush in soil of volume susceptibility 100 times that of commercial $FeCl_2 \cdot 4\,H_2O$.

1.3.3 Development of the SCR-625

By August 1941 the Hazeltine Service Corporation had completed the development of a mine locator,[13, 20] based on an amplified frequency variation at 100 kc, which fulfilled or exceeded (with a few minor exceptions), the

original requirements for a mine detector over average ground. The indicating note increased in pitch and volume as a metallic object was approached, but an exact null directly over the object resulted because of the coil configuration chosen. At that time it was tested comparatively against a metal locator which had been previously developed by the Hedden Metal Locators, Inc., of Miami, Florida, for other purposes. The Hedden locator was called to the attention of the Engineer Board by the National Inventors Council. It, essentially, was an audio-frequency mutual inductance bridge operating at 1,000 c, with a two-coil transmitter-receiver system so arranged that there was normally no "mutual" between the transmitter and receiver. Comparative tests of the two locators indicated that the audio-frequency type was more promising, since its circuits were simpler than the r-f locator. One of the principal objections to the Hedden locator was its extreme height sensitivity. Its detecting sensitivity, too, was probably inferior to that of the r-f detector.

After this demonstration it was decided that Hazeltine should continue the development, using the principle of the Hedden locator.[b]

Description of Instrument

The circuit shown in Figure 1 includes a 1,000-c push-pull oscillator coupled to a pair of transmitting search coils, a receiving search coil coupled to the input of a two-tube amplifier, compensators for reducing to zero the residual search-coil coupling, and visual and audible output indicators. A test circuit, which includes a coil in the field of the search coil, may be closed by a push-button and is used to check the operation of the unit. The portions of the circuit which are grouped in different mechanical divisions are segregated in Figure 1 by dot-dash lines. Any metallic body in the field of the search coils, which ordinarily have a zero coefficient of coupling, couples energy from the transmitting coils to the receiving search coil. The signal voltage is amplified in the receiver, and the output is applied to a rectifier-type output meter and to the audio resonator.

Search Coils. The search coils, shown schematically in Figure 2, consist of three coplanar concentric coils. The radii and numbers of turns of the coils are so chosen that the mutual inductance between the outermost coil and the intermediate coil is numerically equal to that between the innermost coil and the intermediate coil. The outer and inner coils are connected in series with such polarity that their combined mutual inductance to the intermediate coil is very nearly zero. The residual mutual inductance is balanced out by the compensators.

In the sectional view of the search coils, Figure 2, the coils may be numbered 1, 2, and 3, and the radii and numbers of turns may be designated by a_1, a_2, a_3, and n_1, n_2, n_3, respectively. If, as in this case,

$$\frac{a_1}{a_2} = \frac{a_2}{a_3}$$

then $M_{12} = kn_1n_2a_2$ and $M_{23} = kn_2n_3a_3$, in which k is the same constant in both formulas. Letting

$$M_{12} = M_{23}$$

then

$$\frac{n_1}{n_3} = \frac{a_3}{a_2},$$

which is the condition for balance.

If a small metallic object, such as a mine, approaches the search coils along their axis, the resulting coupling between the oscillator and receiver coils increases to a maximum at a distance slightly less than the radius a_3 of the outermost coil. The coupling then decreases, becoming zero at the distance a_2 (which is the radius of a neutral sphere, i.e., a sphere of zero coupling), and increases with opposite polarity as the object comes closer. It is intended that the search coils be held at least 6 in. above the ground when in use in order to reduce the effect of the ground; since a_2 is much less than 6 in., it follows that a mine will always produce maximum coupling when directly under the search coils.

The mutual impedance between the oscillator and receiver circuits is adjusted by means of two pairs of compensators which are very nearly independent. One of each of these pairs provides a vernier adjustment. The mutual

[b] Before undertaking any development work Hazeltine investigated various commercial instruments available for detecting metal objects. In this investigation the Hedden Metal Locators, Inc., a small concern, was overlooked.

reactance compensator comprises an iron core mounted on a screw, permitting it to be moved axially through the compensator, the magnitude and polarity of the reactance depending on the position of the core. The iron core serves to increase the flux through the compensator coils again depending upon the position of the core. It may be noted that residual mutual inductance caused by imperfect balance in the search-coil assembly is the same for harmonics of the oscillator frequency as for the fundamental frequency. Properly designed compensators must

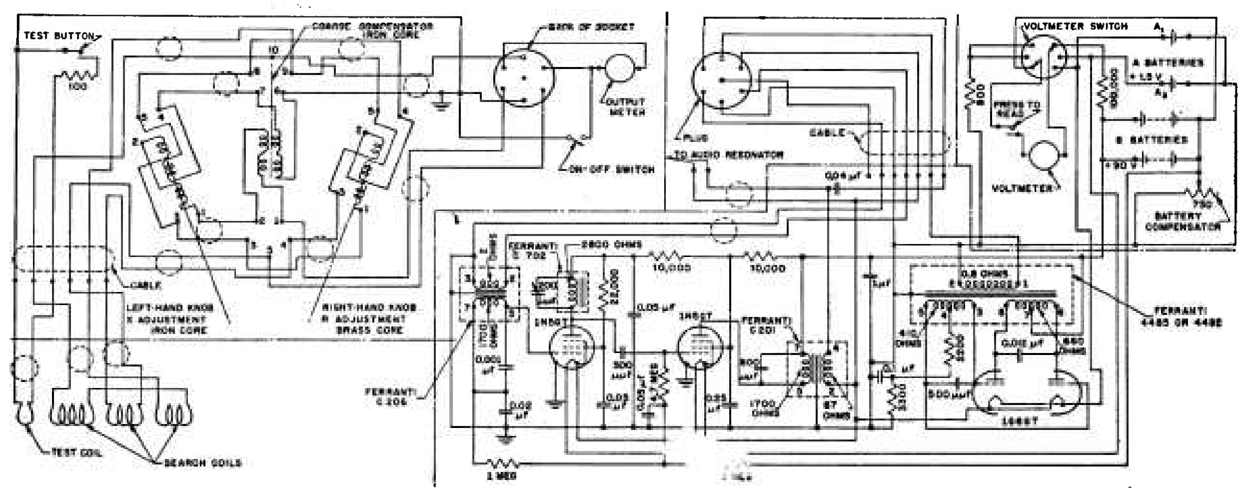


FIGURE 1. Circuit diagram of the Hedden locator.

in its immediate vicinity with little change in the phase of the flux. A brass core moved through the resistance compensators adjusts the mutual resistance between the circuits. The Q of the brass core is much less than 1 (approximately 0.1), so that a component of flux in time quadrature with the exciting field is produced, and mutual resistance is thereby introduced between the oscillator and receiver search-coil circuits, the magnitude and polarity

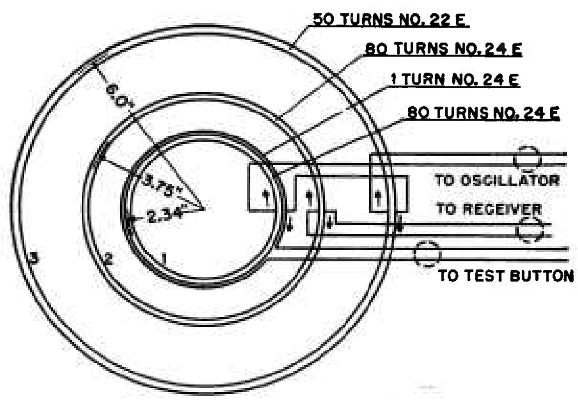


FIGURE 2. Search coils.

obey a given relation in order that the harmonics and fundamental all balance out through the same adjustment.

Oscillator and Amplifier. A push-pull class-B oscillator circuit is used in order to minimize the harmonics and, in particular, to cancel the second. The receiver search coil is coupled to the grid of the first amplifier tube by a step-up transformer. Tuning the transformer secondary increases the gain from the receiver coil to first grid to a voltage ratio of 93 and provides some selectivity. The 1N5GT first amplifier tube is impedance-coupled to the output stage by a tuned choke. The output tube is a second 1N5GT coupled to the earphones and meter by a step-down transformer. The output circuit is a high-pass filter. An increase in audibility and additional selectivity against harmonics and extraneous noise are gained by the use of a 1,000-c acoustic resonator.

General Design Considerations

The problem of detecting a metallic object by a mutual inductance bridge is readily seen to be that of detecting the complex impedance

reflected into the system by a metallic object in the presence of other components of complex impedance due to the proximity of conducting permeable ground. The properties of the soil obviously limit the depth at which an object can be distinguished from ground effects. Magnetic susceptibility and conductivity are the soil properties which are important, the dielectric displacement currents being negligible as compared with conduction currents. In general, there is a borderline frequency below which the susceptibility effect is greater and above which the conductivity effect is greater. The susceptibility effect is independent of frequency[18] while the conductivity effect increases with frequency. The soil susceptibility causes a change of reactance in the receiver coil, just as the object does. The conductivity causes a change of both reactance and resistance, the resistance change being the greater at lower frequencies and the reactance change at higher frequencies. All these relations are functions of the susceptibility and the depth of penetration which involve frequency and conductivity.[18]

Electrical Characteristics of the Ground. The permeability of average ground was at first thought to be near that of free space, but departures from this equality have proved to be the greatest cause of spurious responses in metal locators. Near one laboratory on Long Island the relative susceptibility of the ground averaged 0.001, with many lumps of more magnetic material. The range of susceptibility measurements from these tests varied from 0 to 0.0025. From the performance of the detectors in the field it is apparent that certain soils must be more highly magnetic than the average mentioned above. For example, lava soil and the French pavé were particularly troublesome in the field.

The range of conductivity of ground varies from practically zero to that of sea water (4 mhos per m). The attenuation of the exploring field due to the conducting ground is negligible at a frequency of 1 kc.

The dielectric constant or specific inductive capacity of the ground has been demonstrated to be unimportant in the case of metallic mine detectors operating at low frequencies.

The general importance of the electrical characteristics of the ground may be emphasized by the statement that for high sensitivity the mutual inductance must be neutralized within about 1 part in 3,000,000. This corresponds to a residual coupling of no more than 0.001 μh.

System Analysis. The important factors entering into the choice of a system for mine location are discussed briefly below:

1. Target responses. These may be expressed in terms of coefficients of resistive and reactive mutual coupling produced by metal bodies in the exploring field. The mutual impedance reflected by the target is expressed by:

$$\begin{aligned} Z &= R + jX \\ &= L\omega(k_r + jk_x) \end{aligned}$$

where L is the inductance of a spherical search coil. The relative responses and interferences may be expressed in terms of the coefficients of resistive and reactive response, k_r and k_x.

Case 1. Thickness of target greater than depth of penetration. At high frequencies, or when the depth of penetration of the field in the metal of the target is less than its thickness, $k_r > k_x$.[15]

Case 2. Thickness of target less than depth of penetration. For thin metal shells, $k_r < k_x$ at high frequencies; at low frequency, or with very thin metal bodies, $k_r > k_x$. Obviously there is an intermediate frequency such that $k_r = k_x$.

Case 3. Solid body, radius less than depth of penetration. In this case the coefficients are less definite because of the distribution of the heating loss and the stored energy throughout the metal. In general, $k_r > k_x$.

The above relations should be considered along with reflections from ground in selecting optimum operating conditions.

2. Ground responses. The reflections from conductive and/or magnetic ground are considered mainly for frequencies at which the attenuation is negligible at the depth at which the target is buried. For this condition low-frequency calculations[18] suffice, and the ground effects may be expressed easily in terms of analogous coefficients k_r' and k_x'. The resistive coefficient k_r' is found to be proportional to the ground conductivity and the frequency. The reactive coefficient k_x' is found to consist of two terms, one proportional to magnetic susceptibil-

ity of the ground (which is independent of frequency), and a second term which is independent of frequency at high frequencies where k_r' predominates. This term varies as the 3/2 power of the conductivity and of the frequency at very low frequencies. The effects indicated above are for homogeneous ground. Lumps of magnetic material produce positive components of mutual reactance and coefficients thereof. Ground conductivity reflects substantial interfering components only at high frequencies (above about 1 kc over sea water, and above about 1 mc over ground). The reflections due to magnetic earth and rocks are independent of the frequency.

3. Other spurious responses and general comments. The neutralization of the mutual reactance between search coils is only as good as their mechanical stability. Displacements occur either by slow expansion or contraction due to temperature changes, or by strains or vibration. In two-coil structures (overlapping, mutually perpendicular, etc.) the mutual reactance introduced is large and is in direct proportion to the displacement. Only small changes remain in the triple-concentric-coil construction used by Hazeltine in the SCR-625.[28] Even with this construction, however, the stability of the search-coil mutual reactance limits the sensitivity which may be used in locators sensitive to reflected mutual reactance from the target.

Within 50 yd or so of power lines, low-frequency locators respond to the magnetic field around the line at the fundamental and harmonic frequencies. The fifth harmonic is often large, and locators should be designed not to respond to frequencies of 300 c or less.

Coil arrangements using two equal and opposed receiving coils are available which neutralize the response due to uniform fields. These reduce greatly the response to power-line noise and uniform magnetic soil but produce response patterns for the target which have zero response in some directions (directly over a buried mine) and somewhat reduced response in general.

Screws and other metal parts in search-coil mountings cause response in proportion to their size and their conductivity or susceptibility. Their effects may be neutralized when they are firmly fixed. They should be as far away as possible from points where the exploring field varies rapidly with small displacements. They should be as small as possible and of low conductivity material. They then fall in the category of bodies in Case 3 under "Target Responses." The resistance component of spurious mutual impedance is larger than their reactance.

4. Choice of frequency. The ratio of the responses from a sizable metal target and from conducting ground vary inversely as the 3/2 power of the frequency. Over ordinary ground, the conductivity causes no difficulty at any reasonable frequency. Over sea water, the frequency should probably be less than 10,000 c.

The reflections from ground caused by its magnetic susceptibility are not avoided at any frequency, although the effect may be minimized in some systems.

For the simplest locator, 1,000 c is a satisfactory frequency, since simple amplifiers and circuits and a minimum number of tubes are possible. Such a locator can be of the transmitter-receiver type and will give false indications because of magnetic soil and rocks. For locators responsive only to the reflected resistive component from the target, as low a frequency as will avoid power-line interference is desirable—say 500 to 1,000 c.

5. Choice of coils. All recommended arrangements require the neutralization of mutual reactance between search coils. The search coils should be matched to output and input circuits by transformers. The concentric three-coil arrangement is recommended for transmitter-receiver types where the maximum response is desired directly under the search coils. Overlapping two-coil arrangements can probably be tolerated in devices which are insensitive to drift of mutual reactance.

Special coil structures are available for the neutralization of power-line interference and uniform magnetic ground effects, but these do not have the other advantages of the preceding types. Devices which indicate a target by a change of frequency are less susceptible to interference. This is true, for example, in the

reception of frequency-modulated radio signals.

Special field patterns in direction[9] or in depth can be developed by suitable coil arrangements. For example, the concentric three-coil structure and modifications thereof have zero response at a distance below the plane of the coils equal to the radius of the intermediate coil.[25] The proper coil diameter depends on the distance to the object.

Performance

The performance of the locator in detecting the presence of an anti-tank mine on the axis of the search coils is shown in Figure 3. The target was approximately 8 in. in diameter and 3 in. high, with superstructure removed. Tests in the field indicate that the maximum sensitivity of the locator is greater than can be used in the presence of rocks having appreciable magnetic susceptibility. Under these conditions the response to a mine which is buried a foot deep may become indistinguishable from the response to rocks nearer the surface. The average susceptibility of the soil during the above tests was of the order of 0.001 relative to free space.

a typical system will be given in this section as representative of the "state of the art."

The Problem

Experience with various 1,000-c locators of the simple transmitter-receiver type indicated

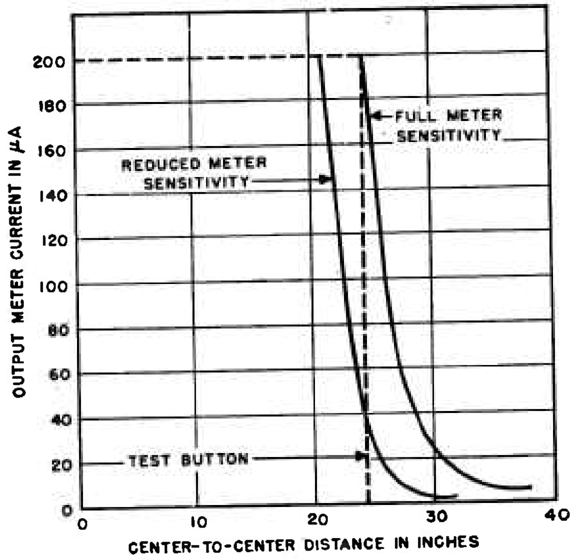


FIGURE 3. Locator performance in the detection of a mine on the axis of the search coils. Sensitivity control set to give 200-μa output with test switch closed and with full meter sensitivity.

two inherent weaknesses: (1) they are sensitive to slightly magnetic rocks or soil and to drift in mutual inductance between the coils; (2) both drift and magnetic ground effects produce coupling components which are nearly pure mutual inductance. These residual responses must be neutralized to the order of 1 part in 1,000,000 for operation at high sensitivity levels. It was thus apparent that a system which responded differently to the mutual resistance reflected by a metal target than to mutual reactance from any source would go far toward alleviating magnetic soil and drift objections.

History

Such a phase discriminating circuit, for an audio-frequency detector, was developed[30] by an NDRC contractor, the Hazeltine Service Corporation, Little Neck, L. I., in the spring of

1.3.4 Phase Discrimination Locators

After the design of the SCR-625 was frozen, it became apparent from further experimental work at Hazeltine that a circuit which discriminated against reflected complex impedance would be, in general, superior for practical use. Such a circuit could reduce or almost completely remove false indications and high-level background noise from magnetic ground and rocks. It was recognized that such a phase discriminating system would probably not be quite as satisfactory for the detection of certain small metallic objects in which the induced eddy-current effect is small. For large bodies, however, this system, which shifts the oscillation frequency by reflected mutual resistance, showed great possibilities. In fact, at the present writing, the phase discrimination type of mutual inductance detector is the most advanced development in metallic mine detection. A brief description of

1942. This was a few months after the standardization for production of the SCR-625. Two to three years later, after the magnetic ground difficulty had proved to be a serious problem in combat use, contractors of the Engineer Board developed phase discrimination systems in order to solve the same problem. These latter systems were not completed in time to be placed in production as a replacement detector for the SCR-625 before the end of the Japanese war. It thus appears as a direct consequence of the cessation of development work by NDRC on solely metallic mine detectors (none of which was done after the spring of 1942) that no improved metallic mine detector making use of the phase discrimination principle reached the field.

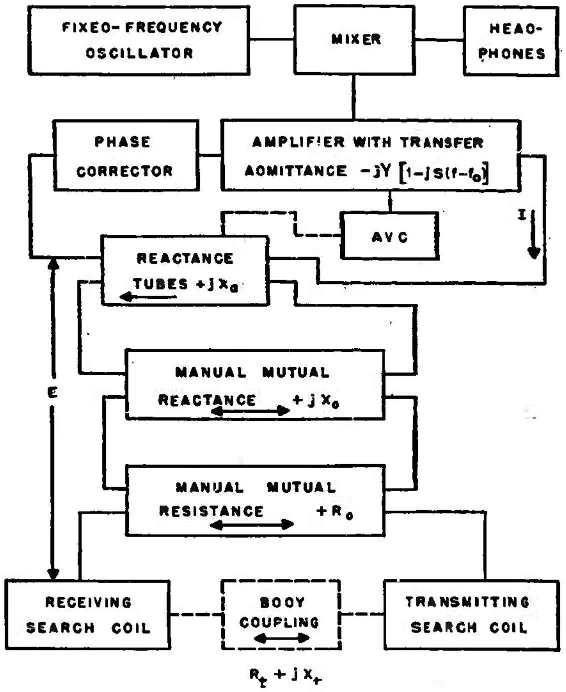


FIGURE 4. Block diagram.

One reason for this unfortunate result was a policy decision on the part of NDRC, in agreement with then existing Army policy, that further development of a metallic mine detector based on the mutual inductance principle was an engineering problem, rather than a research problem, and therefore should properly fall under the cognizance of the Army. The failure of the Army further to explore this principle may in part have been due to a lack of familiarity with the work of NDRC, which, in turn, may have been caused in part by a change in personnel responsible for the NDRC development program.

Method of Operation and Circuit Design

A brief summary of the phase discriminating circuit developed under NDRC contract is presented here as one possible solution of the problem. Reference should be made to the reports on metallic mine detectors by contractors of the Engineer Board for other circuits designed to produce the same results.

The frequency selected for the device was 1,000 c, a near optimum frequency for the detection of bodies of reasonable size because it eliminates effects caused by ordinary ground conductivity. The mutual resistance due to the target is made to shift the frequency of an oscillating circuit. The frequency change is observed by comparing the shifted frequency with a fixed frequency by the beat method. The difference frequency is then detected by a set of earphones. The phase shift is so adjusted that mutual reactance maintains the amplifier in oscillation and affects only the amplitude of the oscillation.

The feedback which produces oscillation is obtained by a small amount of controlled positive mutual reactance between the search coils. The total voltage induced in the receiving search-coil circuit is the vector sum of that due to the controlled mutual reactance and that due to the mutual reactance and mutual resistance of the target. Since the feedback circuit can oscillate only with a net phase shift of zero, the frequency of oscillation changes until the sum of the phase shift in the amplifier and the net mutual impedance between the search-coil circuits is zero.

A block diagram of the circuit is shown in Figure 4 and the complete circuit in Figure 5. The manual mutual resistance R_0 is used only to balance out residual mutual resistance in the circuit in the absence of a target; therefore, the net initial mutual resistance is zero. The phase corrector is used for fine adjustments of

phase so that the initial frequency of the circuit is the same as that of the fixed oscillator (f_0). Alternatively, a frequency adjustment of not limited to the design used with the SCR-625; their sizes should be chosen with reference to the distance at which targets must be de-

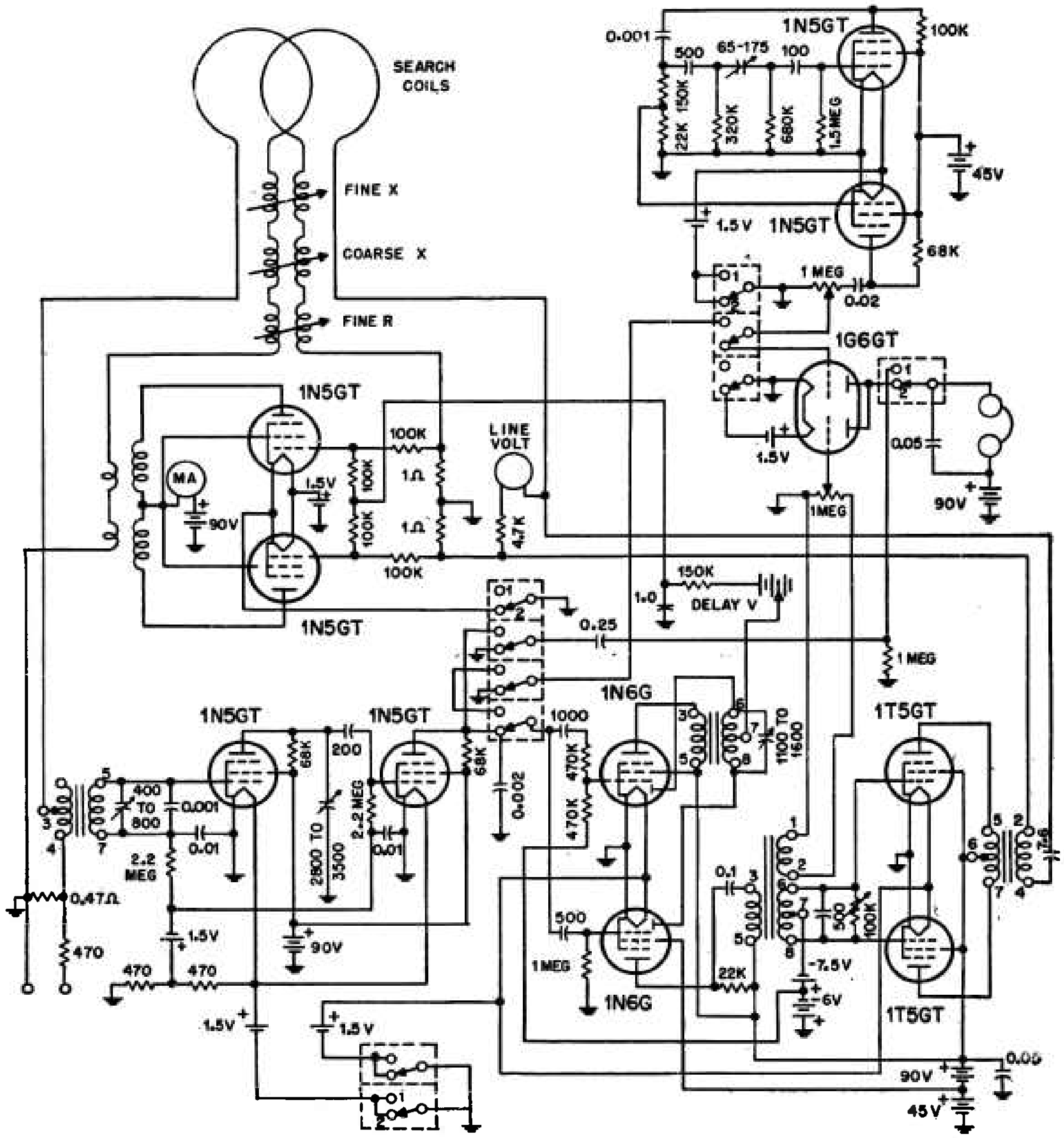


FIGURE 5. Circuit diagram.

the independent oscillator might be used. Once the frequency is corrected, only infrequent readjustments are required.

Coil structures for use with this circuit are tected. Their positions (concentric, mutually perpendicular, etc.) should be chosen with reference to the desired distribution pattern of their exploring fields.[9]

PERFORMANCE

Extensive performance tests were not carried out with this circuit; the following results, therefore, are far from complete. A dummy 8-in. anti-tank mine, buried 23 in. below the surface, was detected easily in magnetic ground with the search-coil disk 6 in. above the ground; it could just be detected with the search coil 12 in. above the ground. By way of contrast, it was necessary to adjust and carry the search coils of a SCR-625 locator at a critical height of about 8 in. above the ground in operation;

FIGURE 6. Disassembled search unit.

the mine could then be detected with great care at a depth of 18 in. in the same soil. No magnetic rocks were indicated by the new locator, whereas the SCR-625 detected many. A powdered-iron ring 1¼ in. in diameter did not change the frequency of operation at any distance from the search coil. Although this ring has small mass, it produced definite indications with the SCR-625 locator at a distance of about 1 ft.

1.3.5 The Portable Iron Detector and the AN/PSS-1

The portable iron detector[1] is an extremely simple device for detecting ferromagnetic objects buried in the earth by means of their distorting effect on the earth's magnetic field. Its major practical importance is derived from the fact that it was the forerunner of the AN/PSS-1, a detector designed for use by swimming members of naval combat demolition teams for the detection of anti-boat mines. The PID was developed under an NDRC contract by the Department of Terrestrial Magnetism, Carnegie Institution of Washington, while its modification to the AN/PSS-1 was carried out under a contract with the Engineer Board.

In principle the PID is a space-time gradiometer consisting of two magnetometers aligned with each other but with their outputs connected in opposition. In this arrangement the effect of the uniform magnetic field of the earth is cancelled out, while the effect of a nonuniform magnetic field, such as that resulting from a ferromagnetic object magnetized by induction, yields a signal that may be amplified and made audible. Thus the application of the gradiometer principle permits the detection of a small anomaly in the presence of a large, uniform magnetic field.

The search unit (see Figure 6) consists of two Permalloy rods 3/16 in. in diameter and 6 in. long, mounted so as to have a common axis and a spacing between centers of about 8 in. Surrounding each of these rods is a coil of 40,000 turns of No. 40 insulated copper wire. The two coils are connected in series opposition with the terminals brought out to an amplifier and indicator. The resultant mine signal from the detector head is a weak, unidirectional emf having a duration of the order of one second.

Figure 7 shows the instrument in operation.

According to the circuit diagram of Figure 8, an emf developed in the search unit passes through two stages of amplification and is used to modulate the output of a 1,000-c phase-shift oscillator. The amplified signal voltage and carrier are applied to the grids of the modulator tubes in such a manner that the modulator output contains only the signal frequency and the side frequencies. Since the signal frequency is very low and the carrier frequency is between 800 and 1,000 c, the side frequencies are nearly the same as the carrier frequency. Furthermore, the side-frequency amplitudes are directly proportional to the amplitude of the signal frequency. The output of the modulator tubes is passed through one stage of audio amplification and fed into headphones through a matching transformer. Distinct pulses of a high-pitched tone are heard by the operator as the search unit passes near a magnetic object.

Factors limiting the usefulness of the PID are: (1) lack of sufficiently precise balance and alignment of the two rod-coil combinations,

(2) insufficient elimination of rotations of the pickup device during a sweeping motion, and (3) the lack of an entirely satisfactory means of amplifying the very small, slowly changing emf developed in the search unit. The sensitivity of the PID to ferromagnetic objects is approximately equivalent to that of a mutual

FIGURE 7. Search unit in operation.

inductance detector, such as the SCR-625; it is, of course, of much simpler design. Certain modifications of the PID, if carried out, would probably increase its range beyond that of a mutual inductance detector.

The AN/PSS-1 is similar to the PID in all fundamentals. Engineering changes have been incorporated, however, such as mechanical rotation of the magnetometer coils and complete waterproofing. It is of interest to note that the Permalloy cores or rods of the PID were removed in the AN/PSS-1. This permitted an increase in the stability of balance, resulting in a net increase in useful sensitivity over that with the rods in place.

The AN/PSS-1 is able to detect anti-boat mines, such as the Japanese J-13, at a range of about 2 ft under water. Careful magnetic gradiometer tests with other instruments indicate that the anomaly due to the presence of such a mine does not extend farther from the mine.

1.3.6 Evaluation of Metal-Detector Program

The design and construction of locator equipment for metallic mines was, for the most part, a straightforward engineering research problem to which there are now a number of satisfactory solutions that vary more in detail than in fundamental principle. At the end of slightly less than a year of development work a locator, the SCR-625, was standardized and in the spring of 1942 was placed in production. This instrument was highly satisfactory except where magnetic ground was encountered, when its usefulness was seriously impaired. As this limitation was recognized in the laboratory prior to field usage, it might be expected that within a year or so production of the original detector would be supplanted by that of a modified locator of improved characteristics. This would be the natural chain of events if development work kept pace with field requirements. However, no basic experimental development work on its improvement was carried out in the year and a half following its standardization. When a project for improvement of metal locators was taken up at a later date by the Engineer Board, the continuity of the original development program had been lost, with the consequence that other contractors were forced to rediscover the design principles which had previously been clearly established. This loss of time accounts in the main for the fact that no detector other than the SCR-625 got into field use from production lines in the United States.

At the present writing it is believed that design considerations for a metal locator are well worked out. This statement applies particularly to locators based on the mutual inductance bridge principle and circuits utilized therewith for discriminating against spurious reactive signals caused by magnetic ground.

Considerably less attention has been devoted to the development of certain special-purpose equipments which have possible military applications; for example, the beach detector, basically a metal detector, can probably be im-

proved very easily in the light of our present knowledge. It is also probable that a number of engineering advances can be made in designing equipment for the detection of ferromagnetic objects.

As a summary, it may be stated fairly that the technical side of the metallic mine locator problem was handled adequately by a number of contractors; looking back, however, it seems clear that the timing of the program could have been improved.

1.4 NONMETALLIC MINE DETECTION

Early in the war it was recognized that large-scale enemy employment of nonmetallic mines would almost completely negate the usefulness of standard metallic mine detectors. The Ordnance Department, ASF, was actively engaged in the development of a nonmetallic mine for use by the Allies, and it was natural to assume that the enemy was following similar lines. This expectation was verified by the trend in enemy mine warfare. The use of fewer metal parts by the enemy in the construction of its mines could be explained not only by the supposition that certain metals were becoming increasingly scarce and by production considerations but also by crediting them with the attempt to reduce the effectiveness of metallic mine detectors. Fortunately, it turned out that only toward the close of the European campaign did the Germans actually introduce completely nonmetallic anti-tank and anti-personnel mines in quantity.

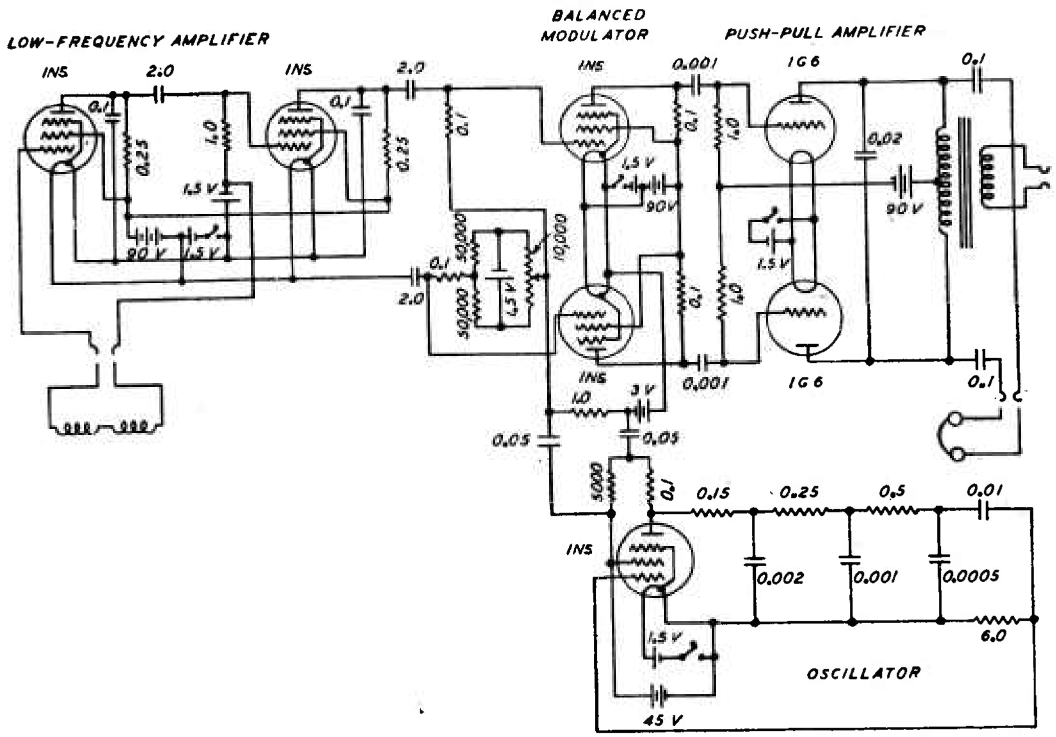


FIGURE 8. Schematic diagram of the portable iron detector (Type AM).

In this chapter the NDRC program on the development of nonmetallic mine locators is described. Although classified here as nonmetal detectors, every detector able to locate nonmetallic mines will also locate most metallic mines under the proper circumstances; to this extent these detectors might be classified quite appropriately as universal mine detectors. This nomenclature is not followed in this report for two reasons: (1) a separate treatment empha-

sizes the nonmetallic aspects of the problem; (2) the detectors described are far less successful in locating metallic mines than standard metallic mine detectors.

The development of a nonmetallic mine locator was officially requested by the Army Engineers under project CE-31 in February 1943. At the time of acceptance no certain method of detecting nonmetallic mines or explosives as such buried in the ground was known. Since the problem was recognized to be of high priority by Section 17.1, it adopted the policy of exploring all methods which appeared to offer any promise of success. These are listed in the following paragraph.

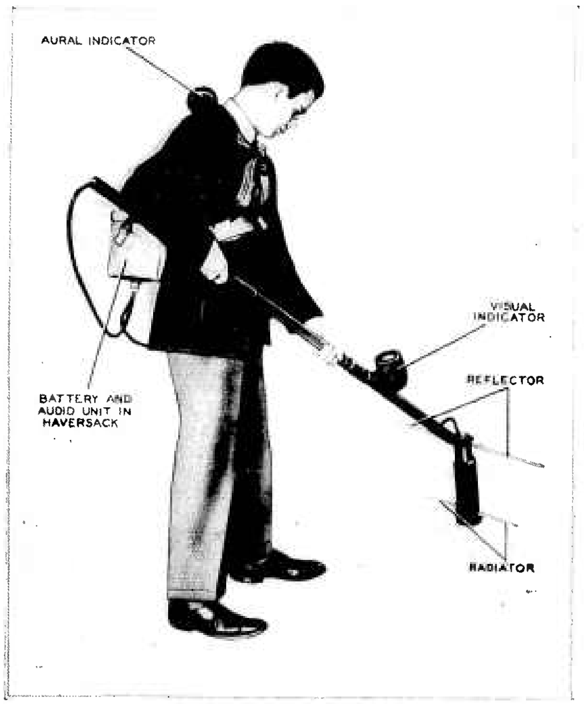


FIGURE 9. AN/PRS-1 detector in operating position.

1.4.1 Possible Operating Principles

1. Seismic methods employing mechanical vibration in the ground under test are based on: (a) variations in the mechanical impedance of the ground, (b) variations in the mechanical transmission characteristics of the ground between two points, (c) reflection of supersonic waves from buried solids to the soil surface, and (d) variation in the earth's "tone" produced by light sharp blows against the ground.

2. Electrical methods are based on the electrical properties of the soil, consisting of: (a) variations in the conductive symmetry of the soil with respect to a normal to the ground, (b) variations in electromagnetic and electrostatic fields induced in the soil, and (c) variations in reflected waves at ultra-high frequencies.

3. Radioactivity methods are based on: (a) variations of the natural radioactivity of the earth due to the presence of a buried object, (b) variations in neutron- and γ-ray emission from the ground when it is bombarded by a neutron source, and (c) variation in the scattering of γ-rays from the ground when it is illuminated by a γ-ray source.

1.4.2 Military Requirements

Initial military characteristics laid down for the detection of nonmetallic mines were necessarily vague and general. The only performance characteristic mentioned was that the detector should detect reliably all nonmetallic anti-tank mines. It was thought at one time that the detector should be able to detect a 5-lb mass of TNT buried 6 in. deep, but this requirement was later discarded as too severe. Military characteristics further required that the device should be portable, simple, and capable of being operated by a man standing, kneeling, or in a prone position. It was stipulated that the weight of the exploring rod should not exceed 10 lb and that of the amplifier and other accessories should not exceed 20 lb. Both aural and visual methods of indication were desired.

For practical field use very severe military requirements exist for a suitable mine detector, either metallic or nonmetallic. The nonmetallic mine detector should, it turns out, be able to detect reliably (meaning practically 100 per cent of the time under all conditions) both anti-personnel and anti-tank nonmetallic mines at operational depths of burial. Furthermore, op-

eration of the detector must be faster than that of manual probing methods. It should be possible to operate the detector at night under enemy surveillance.

1.4.3 Development of the AN/PRS-1

Early in 1943 a prospectus describing possible ways of locating nonmetallic mines was sent to the Engineer Board by RCA-Victor Division, Indianapolis, Indiana. This was referred to NDRC, together with a request that the suggestions be explored and evaluated. After investigation, NDRC awarded a contract to the company, and by the end of the year a satisfactory prototype model of a detector, later known as AN/PRS-1, had been developed and given limited tests. Since that time considerable work has been expended in attempting to improve the AN/PRS-1 by engineering modifications and by more fundamental variations in general design features. The improvements in performance resulting from this work have not been gratifying.

Description of Instrument

The AN/PRS-1, as developed by RCA-Victor, comprises a detector head (see Figure 9) consisting of an antenna structure (radiator and reflector) and a U-H-F oscillator mounted on a sectionalized handle, and a pack (worn on the operator's back) which contains batteries and audio circuits. The U-H-F oscillator, based on a type 955 acorn triode, is an ultra-audion

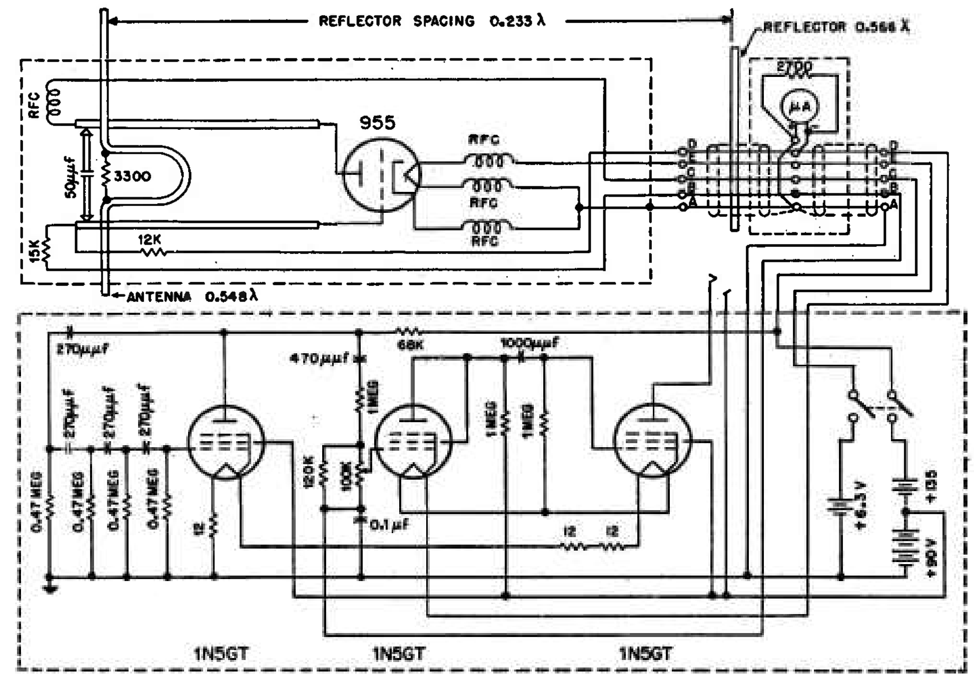


FIGURE 10. AN/PRS-1 detector—schematic diagram, oscillator, and amplifier.

type. The feedback ratio is determined by the tube interelectrode capacitances, which also act as tuning capacitance. An external adjustable inductance between plate and grid provides frequency control and feeds energy at about 300 mc to the dipole antenna by inductive coupling. When the detector head is held close to the ground, as it is when in use, the ground acts as an r-f load which appears as a change in the antenna impedance. Changes in the impedance of the soil thus appear as changes in

the oscillator loading, and are indicated on a grid current microammeter. If the oscillator is operated with enough loading almost to stop oscillation, the grid current becomes sensitive to soil impedance. In addition to the meter, a tone indication in a headset or resonator is produced by amplitude-modulating a 1-kc signal with the grid bias developed by the r-f tube. A schematic diagram of the wiring circuit is

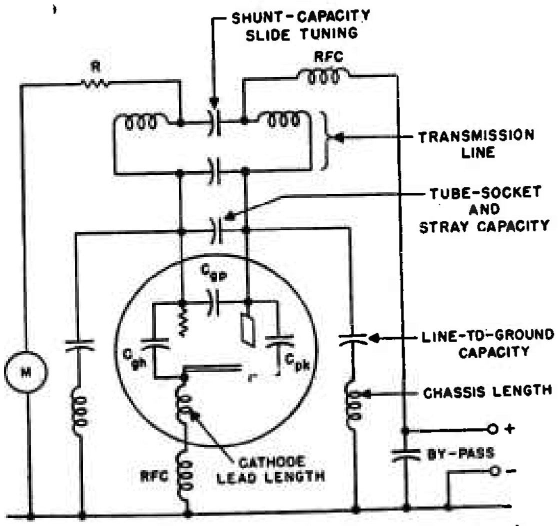


FIGURE 11. Equivalent high-frequency circuit.

shown in Figure 10, and the equivalent high-frequency circuit is shown in Figure 11.

DESIGN CONSIDERATIONS

Relationship of Penetration Depth to Freqency. Attenuation calculations[33, 36] indicate that there is practically a constant depth of penetration of the ground for frequencies in excess of 10 mc. These computations also indicate that for a given frequency the penetration (and, therefore, the sensitivity) of a detector decreases with increasing ground conductivity.

Reflection Effects. The detector produces a steady-state U-H-F oscillation that causes standing waves in the earth and in the air beneath the antenna. It is, therefore, to be expected that the sensitivity of detection will be a cyclic function of the height of the detector above the ground and a cyclic function of the depth of burial of the mine. Depending on the frequency of operation (for example, at 1,260 mc) there may be several heights within the normal operating range at which the sensitivity is nearly zero. The number of such nulls increases with frequency. The cyclic variation of sensitivity with depth of burial, or depth function, is dependent on the electrical characteristics of the soil, the frequency, and the electrical characteristics and dimensions of the buried object. These effects have been computed using Maxwell's equations and have been verified experimentally, as shown in Figure 12 and Figure 13. With reference to these figures, sensitivity to objects is registered by the oscillator as variations greater or less than the average grid current. Points of insensitivity then are spaced one-quarter wavelength apart, or 1.09 in. in water at 300 mc. In Figure 13, M-5 refers to the U. S. Army M-5 nonmetallic anti-tank mine, which is constructed of three general materials: air, glass (case), and TNT explosive. In the depth function a null is found on the surface, and peak sensitivity of detection is obtained at one-quarter wavelength below the surface. Propagation velocity, frequency, and wavelength in any medium are, of course, related by the formula

$$f = \frac{v}{\lambda}$$

in which f is frequency, λ is wavelength, and v is phase velocity.

The velocity in terms of the electrical characteristics of the medium is given by

$$v = \frac{1}{\sqrt{\mu k}}$$

where μ is permeability and k is the dielectric constant.

Resolution. In order to obtain the maximum indication from a mine, it is necessary to have the electric length of the dielectric boundary approximately one-half wavelength or greater, as measured in the medium of least dielectric. This is shown experimentally in Figure 14. This length must be parallel to the dipole antenna because of polarization. From optical theory, and also from the aforementioned experiments, it would be expected that the resolution of a detector system should increase with

frequency. This has been verified, as will be mentioned later.

Conclusions in Determining Frequency of Operation

1. Frequency *relation to mine size.* Since the initial performance characteristics called for detection of anti-tank mines, the M-5 nonmetallic mine was chosen as a representative sample of the type of object it was desired to detect.

2. Frequency *relation to penetration depth.* This consideration does not restrict the frequency choice too much; as has been previously noted, the penetration remains nearly constant for frequencies above 10 mc.

3. Frequency *relation to null-point depth.* Ground conditions are quite variable, the dielectric constant varying from 5 to 25, whereas that for pure water is 81. Peak sensitivity of detection will be obtained at $\frac{1}{4}\lambda$ below the

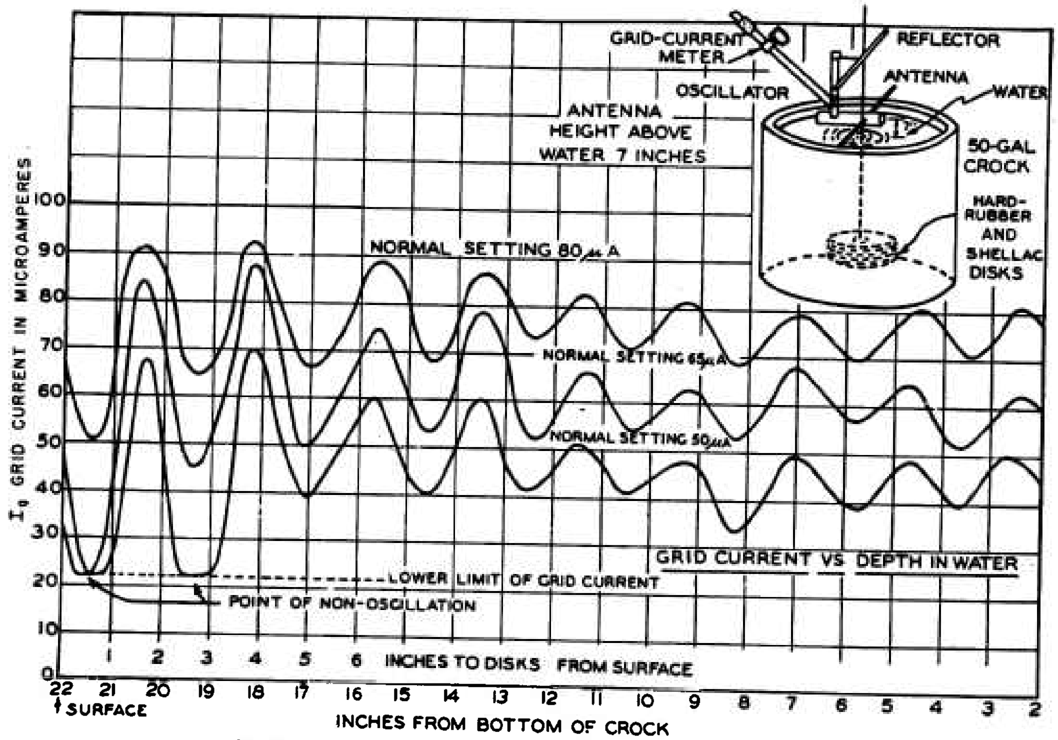


FIGURE 12. Characteristics of detection in tap water.

The properties of the materials in this mine and its dimensions are listed in Table 1. In this mine, air and glass, because of their thickness, do not produce as much reaction as TNT, which is detected quite easily at 304 mc. The use of this frequency tends also to eliminate detection of smaller objects, such as rocks and air pockets, which if detected increase the number of false indications.[c]

[c] It will be noted here that the initial design of the AN/PRS-1 was directed particularly toward the detection of large nonmetallic mines, not toward the detection of small anti-personnel mines, such as Schu mines, which later became most important in the German theaters of operation.

surface. A practical depth for a mine is 3 in., and it therefore follows that a λ of 12 in. is desired in the soil. An average dielectric soil condition is between 10 and 15, indicating the use of a frequency between 310 and 254 mc.

4. Summary. Depth function considerations designate a frequency which is compatible with that chosen (for the M-5 mine) from resolution considerations; these, in turn, are compatible with the penetration effects. There remains to be introduced the cyclic variation in detector height or height function. It may be argued, in general, that increasing the frequency of operation because of the standing-wave patterns

increases the number of nodes per unit distance the detector is held above the ground. It would be expected that increasing the frequency would, therefore, make it more difficult to compensate for variations in detector height during normal mine-sweeping operations. However, by certain design tricks,[33] it was possible to introduce some height compensation into the

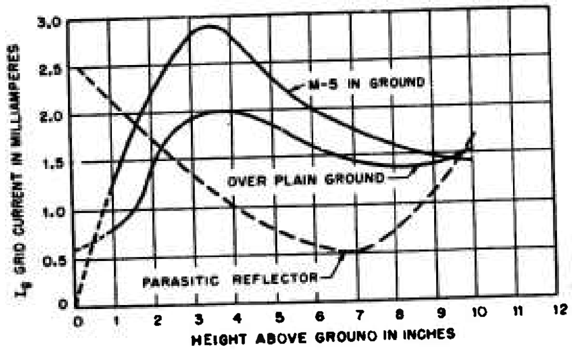


FIGURE 13. Observed data of height and grid current.

AN/PRS-1, giving it a fairly flat characteristic at the normal operating height of 4 in. This compensation is difficult to regulate and is much more satisfactory over dry soil than over wet soil. Thus a fairly satisfactory control of height function can be achieved at 300 mc.

Performance

There are numerous deficiencies in the performance of the AN/PRS-1, some of which can be anticipated from the foregoing discussion. In general terms these deficiencies or limitations may be listed as follows.

False Indications. In operation false indications were encountered because of insufficient height compensation. Considerable care was necessary in sweeping with the detector in order to prevent variations more than an inch or two in height above ground; over uneven terrain such constancy of height was frequently impossible to achieve. More important sources of false indications were roots, stones, recently disturbed patches of earth, etc.—macroscopic changes in the electrical characteristics of the ground which the detector was unable to discriminate against.

Reliability. Except under certain circumstances, the AN/PRS-1 was a reliable detector of both metallic and nonmetallic anti-tank mines. Its sensitivity to metallic mines was considerably less than that of a standard mine detector, such as the SCR-625. It was unreliable in its detection of small anti-personnel mines, e.g., the Schu mine, which it was not designed to detect, and the German S mine. Since detection sensitivity is a function of the depth of the mine below the surface of the ground, under some conditions sensitivity minima can be found at depths typical of actual mine-laying practice. In addition, the AN/PRS-1 performed unsatisfactorily over extremely dry ground (such as dry sand) and over extremely wet ground.

Mechanical Design. The above objections are inherent in the electric system of the AN/PRS-1. Other criticisms of the PRS-1 were

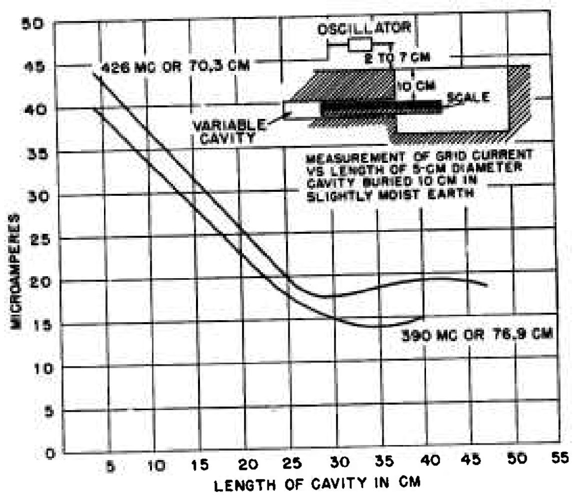


FIGURE 14. Observed data of air-cavity reflection in ground.

based on its vulnerability to mechanical shock and certain engineering design features which were not basic limitations.

Miscellaneous. Miscellaneous objections or limitations include a polarization effect and the necessity for frequent readjustment. Dipole radiation is strongly polarized, thus tending to detect only objects with a dimension parallel to the antenna of 4 in. or larger. Nodal points shift greatly because of varying ground conditions, which may be caused by changes in

the moisture content affecting the dielectric constant of the soil. Adjustments must be made to compensate for these variations.

Advantages of this detector are its ability to operate by being swept over the ground like a metallic mine detector, the simplicity of its circuit, and its ability to detect both metallic and nonmetallic mines. It is perhaps worth mentioning that the AN/PRS-1 is believed to be the only nonmetallic mine detector produced by any of the combatants in World War II, although attempts were made by other countries to design such a detector. It could not supplant the SCR-625 operationally because most of the enemy mines contained some residual metal, which could usually be detected by a metal locator, and because hand probing, though slow, was almost 100 per cent reliable as a means of detection.

TABLE 1. Properties of materials comprising U. S. M-5 nonmetallic mine.

Materials	Diameter (in.)	Thickness (in.)	Dielectric Constant (k)	Velocity of propagation	Frequency corresponding to ½λ of diam.	Thickness corresponding to f (mc)
Air space	10	1	1	3.0 x 10^8 m per sec	590 mc	1/20 λ
Glass case	10	1	6.2	1.2 x 10^8 m per sec	236 mc	1/20 λ
TNT explosive	10	3	3.75	1.55 x 10^8 m per sec	304 mc	1/6 λ

1.4.4 Other U-H-F Detectors and Improvements in the AN/PRS-1

As summarized in the last section, there were certain limitations characteristic of the AN/PRS-1 which prevented it from becoming a useful detector in the field. Logically the next step in the development was to reduce or eliminate design deficiencies so far as possible. Attempts were made not only to increase performance but also to reduce weight, improve ruggedness, and to make other engineering design advances. Toward these ends new U-H-F systems were investigated, and modifications of the AN/PRS-1 system were considered.

The cyclic nature of the height function and the depth function, explained as standing-wave effects, has already been mentioned, as has the expected variation in the number and positions of the nodes of detection sensitivity with frequency. It appeared that if a detector were made responsive at more than one frequency, the nodes of sensitivity could be staggered; and when one frequency was insensitive, another might be at maximum sensitivity. Both RCA-Victor Division, New York and another contractor, Polytechnic Institute of Brooklyn, N. Y., used this as a basis for one general attack on the problem of developing an improved locator. Further consideration of this method led to the conclusion that a higher frequency would be needed if the resolution was to be increased appreciably.

Early efforts thus were directed toward the development of facilities suitable for investigating detector characteristics at a number of frequencies, all higher than 300 mc. First attempts made use of the technique of continuously sweeping over a broad frequency spectrum. Results were somewhat obscured by limitations in the apparatus and technique. Later tests were made at spot frequencies. The results of these tests led to a study of detection characteristics under carefully controlled conditions at a single high frequency. Analysis of results up to this point[35] gave a new perspective: the importance of the depth function appeared to be minimized, and the problem of height compensation stood out as the major objective.

A study of detection characteristics at 1,270 mc confirmed earlier concepts and led to the development of a detector consisting of a source of radiation directed toward the earth and a directive receiver which responded only to signals reflected from buried objects. This approach was carried on at various times[35] independently by the two contractors.[32] The method was known commonly as the Brewster angle

method from the analogy to the optical case, and was studied both at 10-cm and 3-cm wavelength (S band and X band).

In addition to this program, RCA-Indianapolis continued development work using approximately the same operating frequency. Problems included not only increased performance and less weight, but also (1) more precise specifications for elements of the AN/PRS-1, (2) adequate protection for the antenna, (3) a laboratory method of determining and measuring the sensitivity of the detector, and (4) a more easily adjusted detector.

The program described above resulted in the construction of many laboratory detectors which were discarded and replaced by other models as better (or at least newer) ideas were formulated. In the remainder of this section, attention will be confined mainly to a description of the *Brewster angle detector* [BAD] and an evaluation and summary of the results from other investigations. The BAD is discussed separately because, although its development is not completed and therefore its limitations are not well known, it appears to have application as a vehicle-mounted detector. Final models of the AN/PRS-1 type are only briefly mentioned; a more complete description of them is made in the next chapter under universal or combination detectors, as these models do not appear to have an application by themselves. The two-frequency scheme already mentioned will not be discussed further other than to state here that it was tried and discarded independently by the two different contractors for the following reasons: (1) at practical frequencies (S- and X-band ranges) reflections from surface irregularities could not be eliminated[32, 35] or minimized sufficiently; (2) because of high attenuation, the depth of penetration was inadequate for practical use in conductive soils.

AN/PRS-1 Detector Advances

Although extension of the frequency range by a factor of ten higher did not lead to a detector superior in performance to the AN/PRS-1, further investigations at or near the PRS-1 frequency (300 mc) resulted in models definitely superior to it. The NDRC versions of this advance were designated by the Engineer Board as detector sets AN/PRS-1 (XB-2) and (XB-3). Twenty-five units of each of these detectors were to be tested by the Engineer Board and the Engineer School. It was the opinion of NDRC that these detectors did not represent a really fundamental advancement in the art of detection and that there was little likelihood of further engineering changes in the basic U-H-F system resulting in the development of a universal detector capable of satisfactory performance in the field—unless utilized in combination with a metal detector. (Detectors of this type will be described in the next section.) This viewpoint may be divergent from that held by the Engineer Board. A contractor of the Board, who studied the AN/PRS-1 system, has developed a detector set (AN/PRS-4) similar to it which the Board feels has a good chance of being a satisfactory universal mine detector. Field tests will undoubtedly settle the question in the near future.

Brewster Angle Detector

Prior to the work on the BAD the Polytechnic Institute of Brooklyn, which developed the detector described in this section, attempted a number of other solutions, but each had faults equal to or greater than those of the AN/PRS-1. The methods[32] tried were: (1) radiating and receiving two frequencies with a single rectangular horn; (2) radiating one or two frequencies from one rectangular horn and receiving on another; (3) radiating simultaneously from two horns and receiving on a small antenna between them; (4) radiating from a biconical horn and receiving on a small antenna at the axis of the horn; (5) transmitting signals horizontally through the ground by means of a buried antenna or by means of a projecting horn, and receiving the scattered energy from the ground. Thus the contractor had considerable experience with the general problem in the wavelength range of 10 cm before initiating studies of the BAD.

The Brewster angle method is based on the following well-known property of electromagnetic waves: if there be incident upon a boundary between two dielectric media an electromagnetic wave polarized with the electric vector

in the plane of incidence, there is a critical angle of incidence at which the waves will be totally refracted so that no reflection from the surface of one medium occurs. Actually, at this critical angle the reflected wave exists to the extent that, mathematically, it travels down the boundary layer between the two media, but there is no energy associated with this wave. It was felt that if a transmitted wave could be totally refracted into the soil, there would be no interfering signal above the ground, caused by ground reflection, to mask a mine signal. In the presence of a mine or other dis-

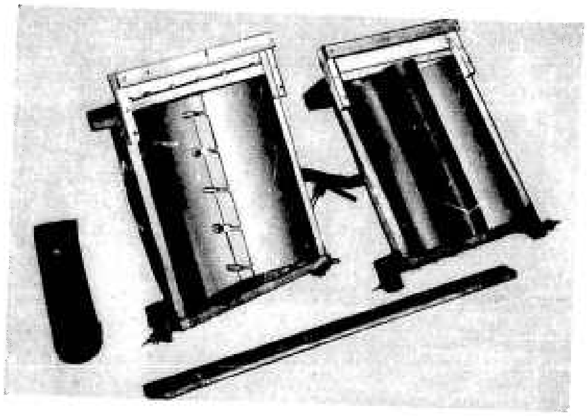


FIGURE 15. Parabolic cylindrical antenna.

turbing object buried beneath the surface, the refracted ray would be partially reflected, this ray in turn being refracted at the ground surface into a properly placed receiver.

Apparatus Description. Photographs of the head of the BAD in its latest developmental stage are shown in Figures 15 and 16. The transmitting antenna, which is connected to a U-H-F oscillator, comprises an array of dipoles placed on the focal axis of a parabolic cylindrical reflector. This method of antenna construction was used in an attempt to obtain nearly plane waves of radiation so that the area illuminated on the ground would be roughly the projection of the reflector area. A similar antenna array was used in the detector head. A portable microwave power source was not developed during the course of the contract, the power source used being a Sperry type 411 klystron, pulse-modulated by a simple blocking oscillator. A clipper amplifier in the detecting circuit was designed to eliminate small spurious signals which were found to be present even under the best conditions. This amplifier is so designed that these small signals are overridden by using a pulse modulation of the high-frequency source and by using an amplifier following the crystal receiver which would not be responsive to signals of low level. The circuit diagram of a semiportable amplifier of an experimental design which fulfilled the above requirements is shown in Figure 17.

Since total refraction takes place at such large angles (75 to 60 degrees) of incidence, direct coupling resulted between the transmitter antenna and the receiver antenna. To balance out this direct signal, a system of compensation was developed, effected by feeding the signal from the transmitter directly into the receiving antenna by a separate coaxial line. A special feedback device was constructed to enable adequate adjustment of amplitude and phase of the auxiliary balancing signal fed into the receiver.

Performance. Extensive tests with this detector in a box filled with sand of varying degrees of moisture revealed it would unerr-

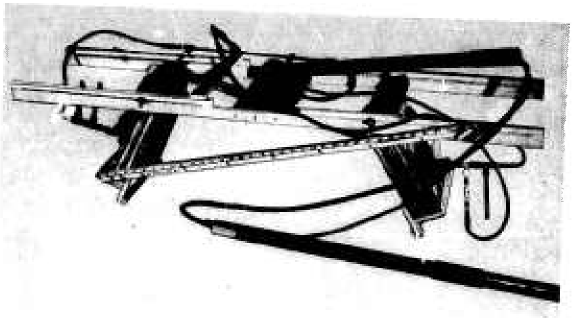


FIGURE 16. Brewster's angle device.

ingly locate a large nonmetallic mine or a small metallic one. Moreover, it did not respond at all to irregularities of the surface of the soil, to variations of height above the sand, or to variations in tilt. Its only drawbacks appeared to be that it would not respond to a small nonmetallic mine, and it would not respond to a mine which had been planted with its flat surface far from parallel with the surface of the soil. Further tests may prove this latter objection to be extremely serious, because it

must be expected that the mines will not be perfectly level in the normal operational planting of mines.

When the device had been dismantled, transported to the vicinity of Sea Cliff, Long Island, and reassembled for field tests, it was found that there was a severe height effect in which false signals were obtained at definite heights above the ground. Location was erratic and the performance in the field was not considered satisfactory. A further test on the instrument after it was returned to the laboratory revealed that it must have been a fortuitous combination of adjustments which had made it operate so

10-cm wavelength, known as the BAD, is still under development. It is not anticipated that this detector will be superior to the AN/PRS-1 type as a portable hand-carried unit, but it is hoped that it may prove useful for some other application, such as a vehicle-mounted detector.

Some advances have been made in the 300-mc range over the AN/PRS-1. Height compensation has been greatly improved. Circuits and mechanical parts have been simplified, resulting in a considerable reduction in weight. However, very little progress has been made toward reliably detecting small anti-personnel mines. In addition to fundamental limitations imposed by

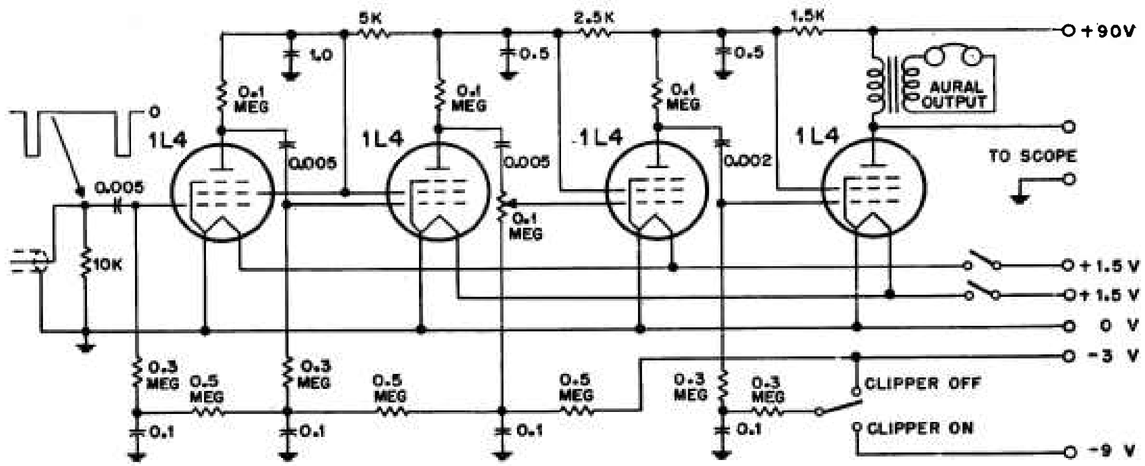


FIGURE 17. Clipper amplifier.

well previously in the laboratory. With the termination of the contract it has been impossible to make a detailed analysis of the behavior of the device in order to account for this variation in results. Since the first experiments reveal that it is possible to obtain adjustments of the equipment which yield very satisfactory operation, it would seem advisable that further work be carried out on this method to ascertain its fundamental limitations and advantages.

SUMMARY

Investigation of the frequency range up to 10,000 mc did not result in the development of a detector superior in performance to redesigned models of the AN/PRS-1 which operate at or near 300 mc. A detector operating at a

wavelength considerations on the size of detectable objects, it was apparent that further increasing the sensitivity of the AN/PRS-1 to yield a better probability of detecting anti-personnel mines so increased the number of false indications that an instrument less useful for field work resulted. It was concluded, therefore, that a U-H-F detector of the AN/PRS-1 type was essentially an anti-tank mine detector rather than an anti-personnel mine detector. Unfortunately, even in detecting the larger mines, modified AN/PRS-1 detectors are not completely reliable for all conditions. Extremely dry soil and extremely wet soil cause major detection difficulties. False indications have been reduced, but they are still annoyingly present.

1.4.5 Seismic or Electromechanical Detectors

One of the earliest attacks on the problem of detecting nonmetallic mines was based on the employment of sonic vibrations in the ground. The three principal variations in this method which were investigated are as follows:[33, 44] (1) detection based on variations in the mechanical transmission characteristics of the earth between two points, (2) detection based on reflection of pulsed vibrations from buried objects to the soil surface, and (3) detection based on variations in the mechanical impedance of the earth.

In investigating the principle outlined in Item 1 above, simple measurements were made of the transmission of a pulse through soil in which a mine was buried, and these results were compared with normal soil. The difference between the two measurements was found to be less than that which could be introduced erratically by variation in the driver and pickup contact with the ground.

There were two outstanding difficulties in obtaining reflection indications (Item 2 above): the very high rate of absorption by the ground of a steep wave front, and the generation of spurious waves within the ground by the driving mechanism. The wave form of pulses transmitted through the ground was observed, and after several unsuccessful attempts to obtain intelligible reflections, work on this system was discontinued.

The method indicated in Item 3 led to the design and construction of nonmetallic mine locator equipment. Two different laboratories, the Sun Oil Company Geophysical Laboratories, Beaumont, Texas, and RCA-Victor Division, Indianapolis, independently designed instruments based on the mechanical impedance principle. Both designs were practically identical. In practice these detectors were able to locate both metallic and nonmetallic mines, but certain limitations in performance (described later) prevented them from becoming useful field equipment.

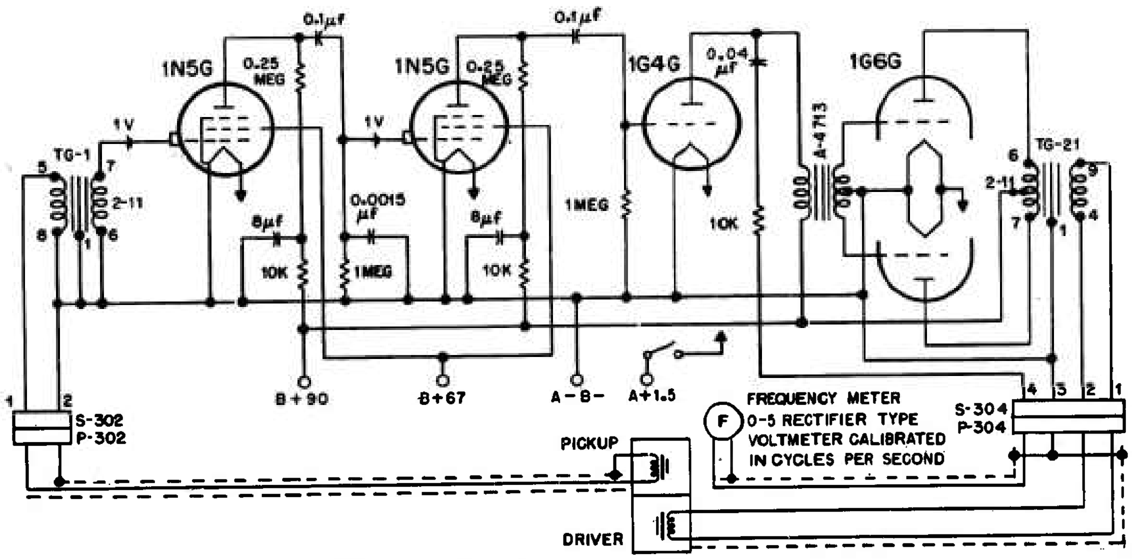


FIGURE 18. Circuit diagram of instrument.

INSTRUMENT DESCRIPTION

These detectors comprised essentially: (1) an oscillating mass, capable of being electrically driven, held in contact with the ground, (2) a vibration pickup device mounted on the oscillator, and (3) an electric network—a feedback amplifier connecting oscillator and pickup. These elements, together with the ground immediately under and surrounding the detector, constitute a resonant system. Whenever

ground conditions are changed by the presence of a mine or disturbed earth, the resonant frequency is usually low; when the ground is normal, the resonant frequency is higher.

A circuit diagram for one of these detectors is shown in Figure 18, and photographs of the apparatus are shown in Figures 19 and 20. The shift in the resonant frequency charac-

FIGURE 19. Prototype instrument.

teristic of such a system is shown in Figure 21. This frequency shift may be observed on a simple frequency meter or may be indicated as a tone in a headset.

PERFORMANCE AND EVALUATION

Unfortunately, a point-to-point investigation of the ground is necessary with this equipment since the range of the seismic detectors is limited to approximately 6 in. from the point of contact. With this range it has been estimated that a 3-ft strip of ground can be checked at the rate of about 15 fpm. It is doubtful that these detectors can compete with prodding from the point of view either of reliability or of speed. One further limitation is that contact with the ground is necessary. Since the transducer heads may weigh 6 lb or more, it would be dangerous to operate them in areas containing low-pressure-functioning anti-personnel mines.

Models of two different types of mechanical impedance detectors (25 of each type) were procured for field trials by the U. S. Army Engineer Board. The above limitations, brought out by these field trials, plus the high promise shown by the AN/PRS-1 type of detector, forced the decision to discontinue work on seismic detectors at that time.

1.4.6 Detector Set AN/PRS-5 (XB-2) (Beach Detector)

The development project which resulted in the design and construction of the beach detector was initially aimed at exploring a method of detecting nonmetallic mines by observing

FIGURE 20. Prototype instrument as adapted for use when crawling.

short-distance changes in ground resistivity using a contact method, the electrodes being metallic wheels pressed hard against the ground. Several wheel-electrode arrangements were made and circuits suitable for use with them devised. It was found that mines could be detected in certain types of soil, but that in many others detection was difficult or impossible.[3, 43] Thus, early in the project, attention

was turned to further investigations of apparatus employing an inductive method in which no direct contacts were made with the ground, a modification of the mutual inductance bridge-type detector. This program resulted in the development by the Electro-Mechanical Research Company, Houston, Texas, the NDRC contractor, of the beach detector, designated AN/PRS-5 (XB-2) by the Engineer Board.

Description of Instrument

Figure 22 is a photograph of the completed detector.[2] Figure 23 is a schematic diagram of

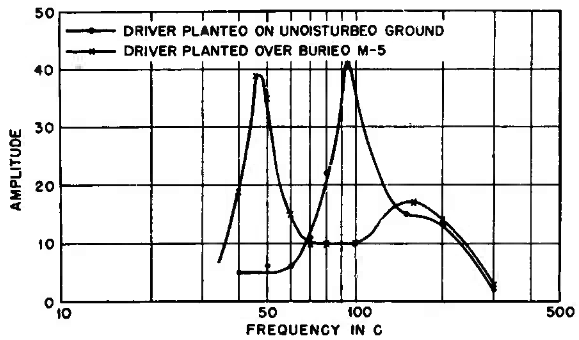


Figure 21. Curves to show frequency characteristics of transducer off of and over M-5 mine buried 3 inches deep.

the layout with the coil system shown in more detail. Figure 24 is a block diagram of the complete circuit, and Figure 25 is a simplified circuit diagram for the detector set.

The outstanding characteristic of this detector is its ability to detect both metallic and nonmetallic mines on beaches and in other soils where the soil conductivity is extremely high. This characteristic is, of course, primarily due to the choice of an r-f (465-kc) energizing field, which, in terms of the analysis previously given, enhances the eddy-current or conduction effect in detection.

The circuit design contains a few novel features which are important in the operation of the detector. First, a type of phase discrimination system was introduced to discriminate against the inductive reactance signal, for reasons which have been mentioned before. Phase selection (see Figure 24) is obtained essentially by the introduction in the circuit of a strong, permanent resistive component which combines in the receiving coil with the signal from the ground and from a mine. Vector combination of complex voltages is used to make the detector less sensitive to inductive signals; that is, the combined emf from the mine signal, ground signal, and permanent resistive component is applied to an amplifier which automatically reduces the total emf by an amount corresponding to the permanent component. The output signal, therefore, measures the changes in magnitude of the impressed emf, the signal being larger for a resistive change than for an inductive change (out of phase) if the two changes are of equal magnitude. The final circuit is then a derivative type, which makes detection possible only if the detector is in motion above the mine (not if it is

Figure 22. AN/PRS-5 (XB-2) Beach detector.

held in a static position). Second, an automatic balancing system is utilized which quickly compensates any unbalance appearing in the circuit. Thus, sweeping over a mine results in a vigorous signal for one direction of sweep, whereas there is a double and less vigorous signal in the opposite direction. One advantage

of the automatic balancing system is to minimize the importance of drift and other factors which make frequent rebalancing necessary.[2, 3]

PERFORMANCE AND EVALUATION

The overall performance of the AN/PRS-5 (XB-2), or beach detector, compares very favorably with the SCR-625. Its main advantages are: (1) its ability to detect all types of mines, both metallic and nonmetallic, in conductive soils, and (2) its partial discrimination against unwanted inductive signals from magnetic soils. Over ordinary terrain the detector has slightly less sensitivity for metallic objects than the SCR-625.

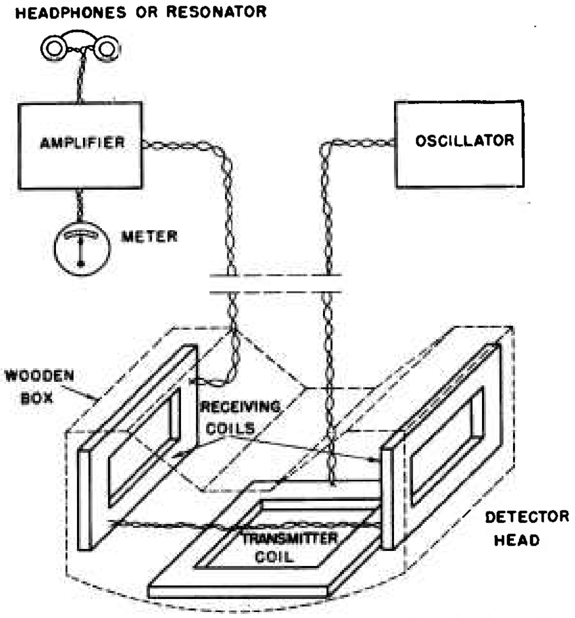


FIGURE 23. Schematic diagram of AN/PRS-5 (XB-2) detector (Type SW-7).

Three models of this detector were constructed and tested at various Army field stations. These trials indicated that the AN/PRS-5 (XB-2) might have application as a special detector for amphibious operations due to its excellent performance on beaches. The Army and Marine Corps decided, however, that the need for this locator was outweighed in importance by the undesirability of adding further special-purpose equipment—even though it was pointed out that the device is a capable metal detector at all times. In case a future requirement for the beach detector arises, it should be noted that its performance can be markedly improved, particularly with regard to phase discrimination.

1.4.7 Earth Current Detector

The development of a system of mine detection in which the required electromagnetic energization is supplied at a distance from the immediate location, the detector itself being without an energizing field, was first extensively considered by the British. Their work resulted in the development of the British detector set X-7, a unit capable of detecting metallic mines reliably. The British lack of success with this set in detecting nonmetallic mines, together with the cumbersomeness of the equipment, at first deterred Section 17.1 from investigating the possibilities of this method further. Two factors were responsible, finally, for the decision to attempt a solution using this approach: (1) a German intelligence document was captured in which was described a countermeasure against Allied mine detectors—this countermeasure was a mine actuated by the electromagnetic field surrounding a detector; (2) the general lack of success of other contractors in making significant improvements in the U-H-F-type detector or in developing new systems with superior performance.

In the so-called earth current method a large loop of cable or, alternatively, an electrode configuration capable of establishing currents along the surface of the soil is used. Anomalies in the field established by the energy source are then detected by a sensitive pickup, such as a coil system, at a distance from the source. (Countermeasure considerations involved in this detection method are discussed in Section 1.6.2.) Contracts were let in April 1944 to two research laboratories, the Shell Oil Company and the Elflex Company,[4] both of Houston, Texas, for the development of the earth current detector. Work on both developments was in progress at the close of World War II. Although these projects were not finished, the work which

was completed permitted the drawing of rather important conclusions concerning the possibilities for detection by this general method.

The sensitivity of the ECD performing most satisfactorily at the close of the project may be summarized as follows.[42] With an estimated exciting field of 100 microgauss in the area under test (3 amp flowing in a two-turn loop). the depth of detection for an 11-in. diameter, ⅛ in. thick iron disk is approximately 2 ft; for a 3½-in. OD, 6 in. long piece of iron pipe planted with its axis vertical, the depth of detection is 1½ ft; for a 3½-in. OD brass tube of ⅛-in. wall, 8 in. long, it is only 6 in. A 6-32 iron screw, ¾ in. long, planted vertically flush with the surface, is just detectable. A similar brass screw has no effect. The a-c frequency of the power source during these observations was 1,000 c. Figure 26 is a photograph of the pickup which yielded the above results. It is believed that the general design of the pickup itself is very nearly satisfactory for the frequencies involved. Compensation or balancing of this pickup is believed to be sufficiently good to allow approximately a tenfold increase in exciting field strength. Thus with the above sensitivities, detection at considerably greater depths of burial can be achieved.

Theoretical considerations indicate that little hope is justified for the detection of insulators with audio-frequency methods. They indicate, further, that nonmagnetic conductors must exceed a certain mean horizontal cross section, depending on their resistivity and the exciting frequency, if their effect is to be comparable with that of a ferromagnetic object of the same size and shape. It is possible that much higher frequencies will yield more satisfactory results in the detection of nonmetallic mines.

Although to a certain extent specialized equipment, the ECD development appears to be worthy of further investigation. It is quite possible, particularly in view of British experience, that the detector would be useful simply as a metal detector. Its countermeasure aspects further support the desirability of exploiting the method. It also seems reasonable to investigate the possibilities of the employment of a higher frequency for locating nonmetallic as well as metallic mines.

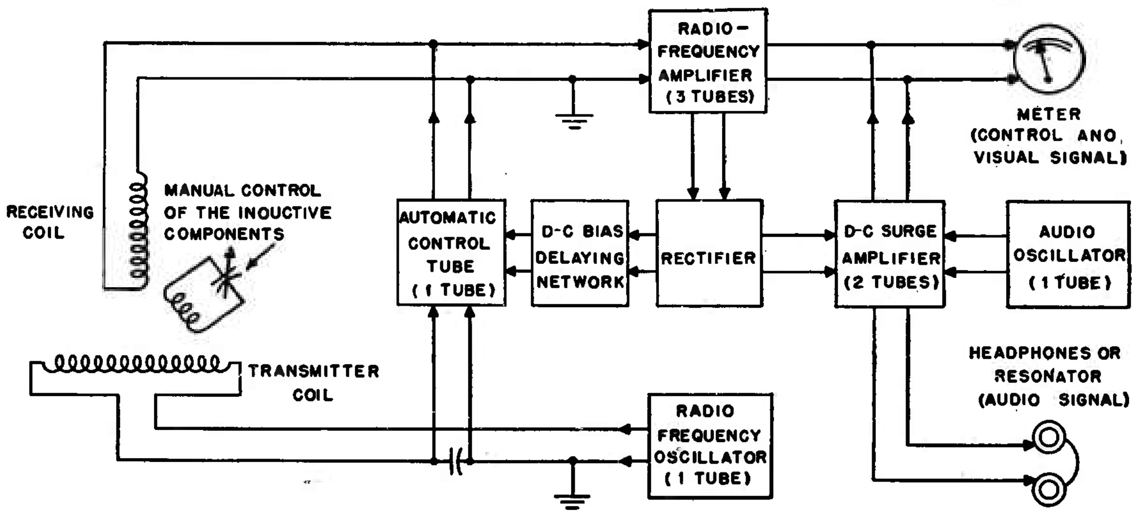


FIGURE 24. Block diagram of complete circuit.

1.4.8 Radioactive Detectors and the Marking of Friendly Mines

INTRODUCTION

This section is concerned with two quite separate problems linked together by the use of a common instrument—a γ-ray detector or Geiger-Mueller counter. Project Mamie was the

extension of the general principle of radioactive tracers to the marking and subsequent identification and location of military materials, especially booby-traps, anti-tank mines, and lanes through minefields. Its most practical application in World War II (albeit German) was to the marking of nonmetallic, anti-tank mines so that friendly troops would be able to relocate them easily. Project Dinah, as the whole nonmetallic mine-detector program was known,

The Mamie problem, which involves the development of a safe, inexpensive, radioactive substance to serve as markers, and a rugged but very sensitive γ-ray detecting device, was solved adequately by the use of activated cobalt-60 in the form of small buttons, and through the use of a modified Geiger-Mueller counter. The conclusion of the Dinah investigation was that nonradioactive, nonmetallic, anti-tank mines, when buried 3 in. under ground, cannot

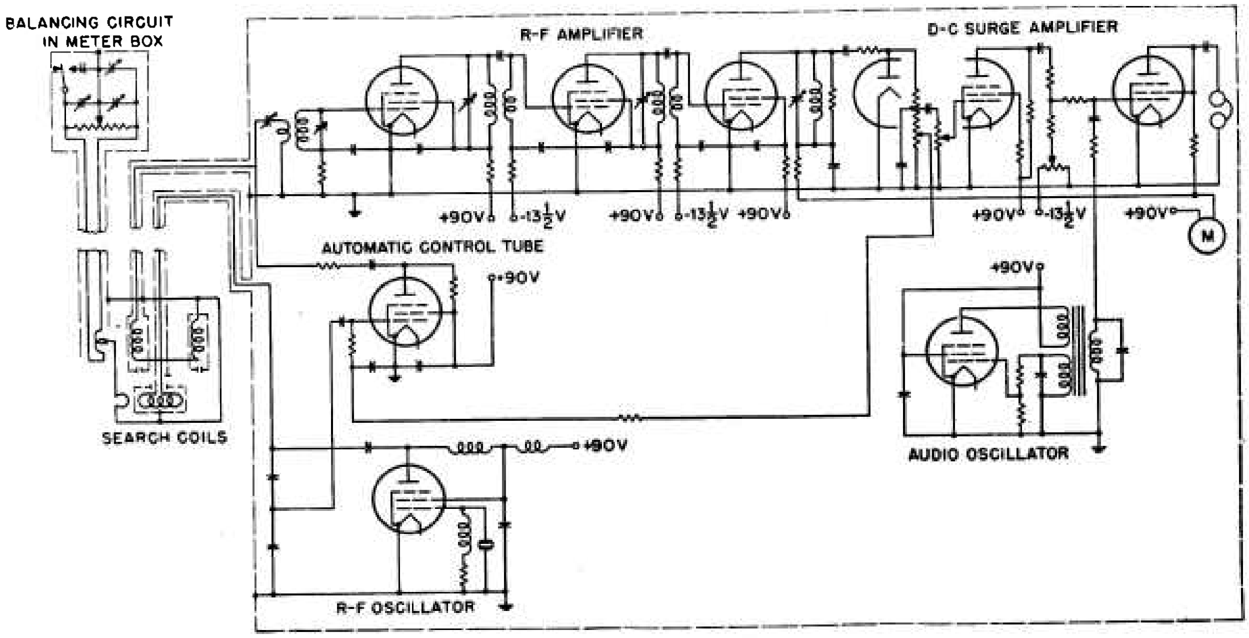


FIGURE 25. Simplified circuit diagram.

included an extension of the principles of radioactivity to the detection of enemy nonmetallic mines. In this, three general methods were investigated: (1) detection due to the shielding effect of a mine on the natural radioactivity of the ground, (2) variations in the scattering of γ-rays from the ground, and (3) various effects associated with the bombardment of the ground by neutrons.

Detection in this last case might be based on: (1) measurement of direct neutron scattering, (2) detection of γ-ray emission occurring instantaneously during bombardment due to neutron reactions, or (3) measurement of γ-ray emission after neutron bombardment has ceased, this emission being due to the production of artificial radioactive elements.

be detected at practical scanning speeds by any of the methods attempted.

MAMIE OR AN/PRS-2

The most sensitive of the γ-ray detectors was standardized and placed in limited procurement by the Office of the Chief Signal Officer. The detector, known as the AN/PRS-2 by the Engineer Board, is shown in Figure 27. It was developed by the Texas Company's Geophysical Laboratory at Houston, Texas.[46] It consists of three parts: a head (which is the γ-ray detector proper), a box (which contains the power supply and amplifier), and a set of earphones. For the γ-ray detector a special instrument is used, the principle of which was not disclosed by the Texas Company. (It had been developed

prior to the NDRC contract.) It is known that the detector operates along the lines of a Geiger-Mueller counter, but it has a much higher efficiency than an ordinary counter for γ-rays. The detector is of all-metal construction and is cylindrical in shape, with a diameter of 2 in. and a length of 4 in. Current pulses from the detector are amplified and equalized with regard to their amplitude and width. The frequency of the pulse is an indication of the intensity of the γ-ray field. Instead of measuring the frequency, the pulses are fed into an integrator, the voltage output of which is proportional to the pulse frequency and, therefore, to the γ-ray intensity. The magnitude of the voltage is indicated by an audible tone, its intensity increasing with increasing γ-ray intensity. A circuit diagram for the instrument is shown in Figure 28.

FIGURE 26. ECD pickup in operation.

The sensitivity of the detector is such that it can very easily detect 2 microgram (μg) equivalents of radium buried 2 or 3 in. in the ground. It is interesting to note that this sensitivity is approximately the same as that of the German detector, Stuttgart 43, designed for the same purpose, i.e., marking of their Topf mine.

The radioactive markers were designed and produced by another NDRC contractor, the Radiation Center, Department of Physics, Massachusetts Institute of Technology,[31] which also investigated the Mamie and Dinah problems from the radioactivity viewpoint. The markers were supplied in one case as a solution of cobalt-60 chloride in small glass ampoules containing 2.5 microcuries (μc), which could be buried intact near or over a friendly mine. According to the work of this contractor, 1 μc of cobalt-60 equals 2.0 μg "radium γ-ray equivalent units." The arbitrary definition of "radium γ-ray equivalent units" in this case is taken to be the relative γ-ray intensity of the cobalt compared with the γ-rays of 1 μg of radium element in equilibrium with its decay products, when both γ-rays are filtered through 1.1 cm of lead and measured on a platinum-screen-cathode counter.

There are, of course, a number of variations in the way a radioactive cobalt could be supplied as a marker. Toward the close of the program, markers were supplied in the form of artificial rocks containing activated cobalt. These rocks were spheres of a porous ceramic material saturated with an aqueous solution of cobalt nitrate which was subsequently converted to the oxide by ignition (so that the cobalt would be insoluble). As described in the literature,[48, 49] activated cobalt does not present the health hazard of radium because (1) it is not biochemically similar to calcium as radium is, and (2) it emits no α-rays (which subsequently destroy the bone-regenerating cells).

DINAH

The following is a summary of the conclusions drawn from the investigation of radioactive methods of detecting enemy mines. It was on the basis of these conclusions that the entire method was discarded.

Shielding Effect Principle. The application of this principle is impractical for two reasons: (1) the observation time[d] for a measurement is prohibitively long; (2) the enemy mine, as is the case with some American M-5 mines, may

[d] It will be remembered here that the accuracy of counting for all counter tubes is proportional to the counting time. Thus, in attempting to distinguish between two counting rates which are slightly different, the time of counting, since it is a statistical problem, enters as an important factor.

carry an amount of radioactive contamination which is too large to present much of a contrast to the surrounding soil.[46]

Scattering of γ-Rays. The method is applicable only in a few restricted cases.

Scattering of Neutrons. The penetrative power is limited. Measurements are affected by the distance between the instrument and the ground, and they depend very much on the water content of the ground.

γ-Rays without Time Delay from Neutron Bombardment. The observed effects have nothing to do with neutrons, and they can be ascribed to the variation in the geometrical arrangement of the measuring instruments.

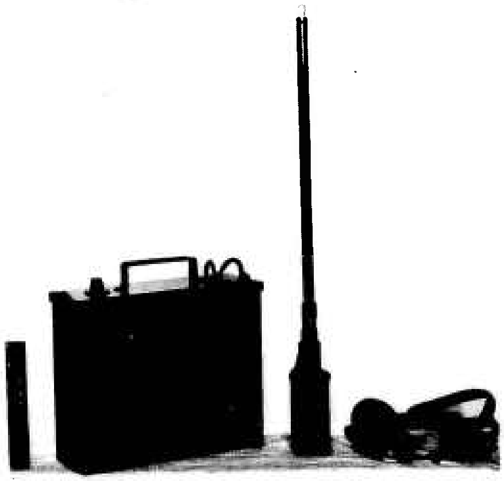


FIGURE 27. AN/PRS-2 detector (Mamie).

Delayed γ-Rays from Neutron Bombardment. The effect is only of the order of the variations one finds over different parts of undisturbed ground. The measuring time is too long.

1.4.9 Evaluation of Nonmetallic Mine-Detection Program

The development of a locator of nonmetallic mines which will meet military field requirements is admittedly a difficult problem. The physical contrast between a mine and the soil in which it is buried may be small, and the difference between a rock and a buried mine usually is indistinguishable. A number of partial solutions resulted from the NDRC program. The most satisfactory of these was the AN/PRS-1 type, which was procured and delivered to the theaters of operation. This detector does not meet all military requirements, mainly because it is not 100 per cent reliable in the detection of both anti-personnel and anti-tank nonmetallic mines. The seismic detector is capable of locating both metallic and nonmetallic mines at shallow depths of burial. It does not constitute a satisfactory detector because of its limited area of coverage and because contact with the ground is necessary. The beach detector has only very limited application for nonmetallic mines (namely, when planted in highly conducting soil), although it is a good metal detector.

That a completely adequate solution was not achieved, it is believed, is due to the inherent difficulty of the problem rather than any lack of resourcefulness or ingenuity on the part of NDRC, the Engineer Board, and their various contractors. Indeed, as compared with the progress made by other nations, the U. S. program resulted in by far the most satisfactory solution, and this solution was available for field use in time to affect the course of World War II, should it have been needed.

The development program carried on by NDRC was not one of great magnitude. At various times nine different contractors, representing geophysical development laboratories, research laboratories of the electronics industry, and laboratories of educational institutions, investigated means of solving the problem. The total NDRC expenditure on these contracts, including the procurement of small numbers of pilot models, was somewhat less than $500,000.

It is possible that more significant results might have been obtained if NDRC had pursued the policy of concentrating the work in one large laboratory, rather than using a diversified series of contractors. In August 1945 plans were under way to attempt, even at that late date, a consolidation of effort in a single NDRC laboratory at the Engineer Board, Fort

Belvoir, Va. In retrospect, it is difficult to see how such a laboratory in this case would have significantly affected the final results, although there appeared to be general agreement among representatives of NDRC and the Army that such a laboratory, staffed with first-class personnel, would have expedited the program at that stage.

It seems clear at the present writing that no fundamental changes or advances in the technique of detection of nonmetallic mines are now in prospect on the basis of methods tried during World War II and described in this report. As the problem is a continuing one which undoubtedly will have to be met in any future war, it is apparent that there is an urgent need for new approaches and new ideas.

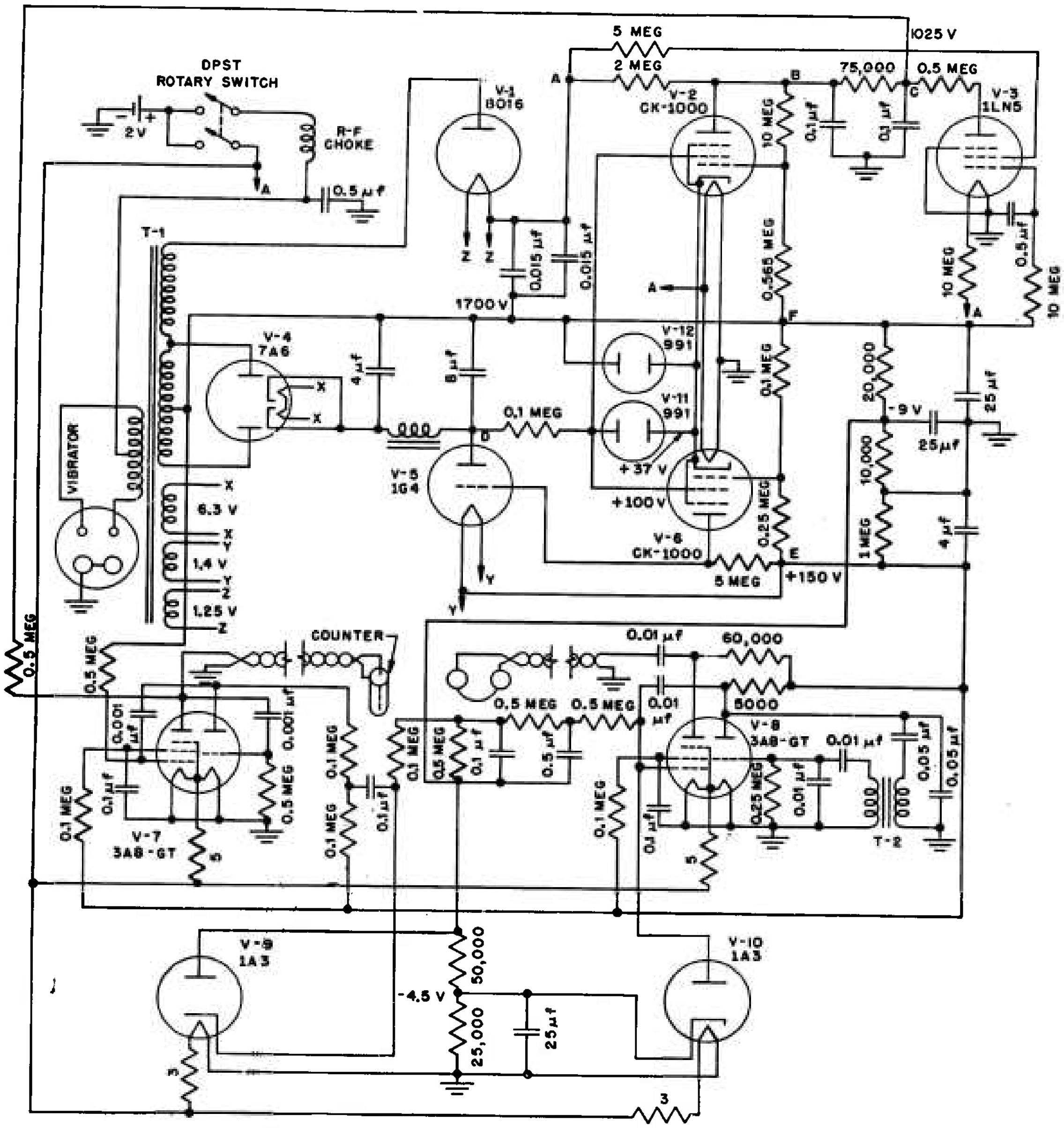


FIGURE 28. Circuit diagram of AN/PRS-2 detector.

Perhaps the most adverse criticism, if one

need be made, of the nonmetallic detector development program is one of its timing. Not long after the AN/PRS-1 was in production it became apparent that this detector would not adequately fulfill all the military requirements, and result in a more useful field detector. However, a year after these models were first made, the design of combination detectors was in the same state of development because no further work was done with them. The failure to pur-

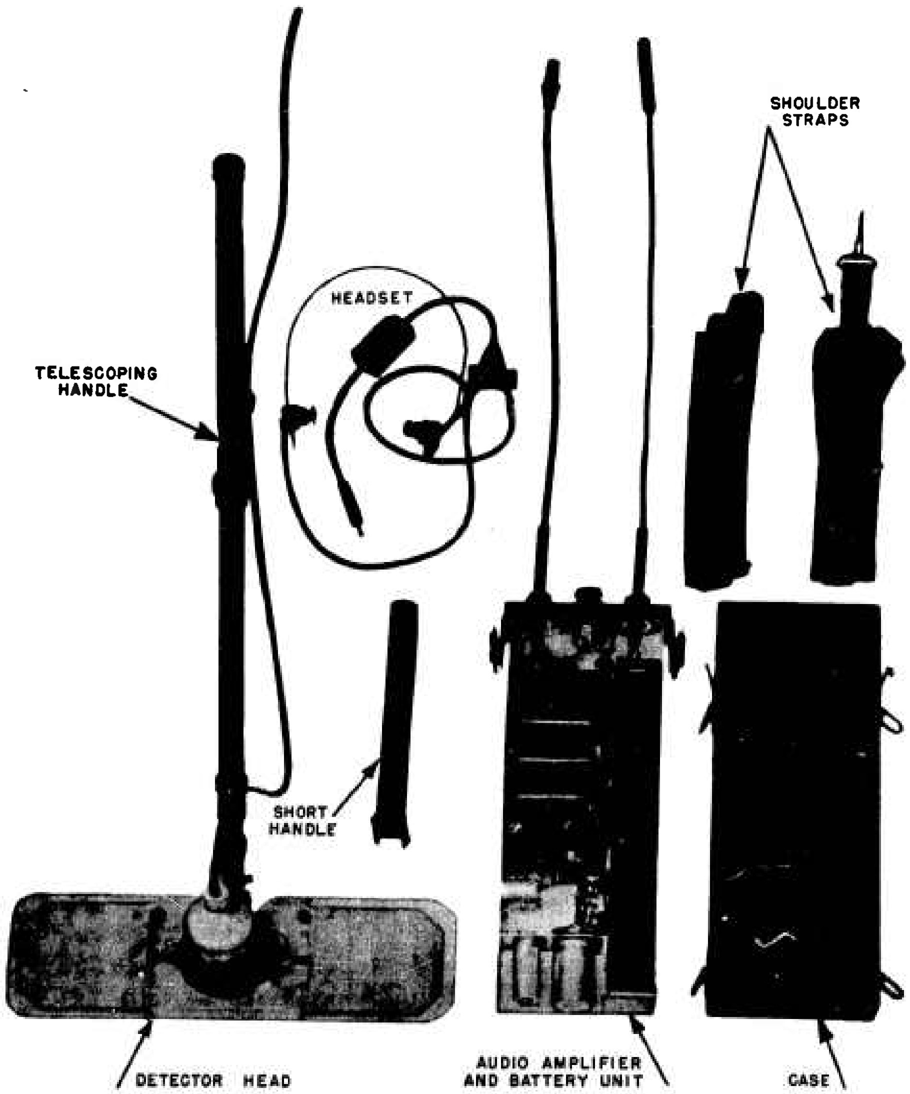


FIGURE 29. AN/PRS-1 (XB-2) detector—set components.

and it was shortly thereafter that combination models of the AN/PRS-1 with available metal detectors were constructed by various NDRC contractors. These models, as will be described in the next section, apparently eliminate some of the limitations inherent in the AN/PRS-1 sue this promising engineering advancement was probably due to the fact that NDRC and the Engineer Board were counting heavily on improvements in the design of the AN/PRS-1 type of detector to meet field objections. Toward the close of the program every effort was made

to expedite the design and construction of these units and to make up for the time lost.

1.5 UNIVERSAL MINE DETECTION

1.5.1 Introduction

The ultimate objective of a mine locator research program is the development of a detector that will locate under field conditions all types of mines in use by the opposing forces. Such a device, which may be termed a universal mine detector, has been the goal of the research program of the Engineer Board and Section 17.1, NDRC. The closest approach to a universal detector developed by NDRC is the combination detector described in this chapter. This detector is simply an amalgamation of a U-H-F detector and a metal detector. The U-H-F part of the combination locates nonmetallic mines (with the same fundamental limitations already described), and the metal-detecting portion locates metallic mines and mines which, though perhaps mainly of nonmetallic construction, do contain some metallic parts.

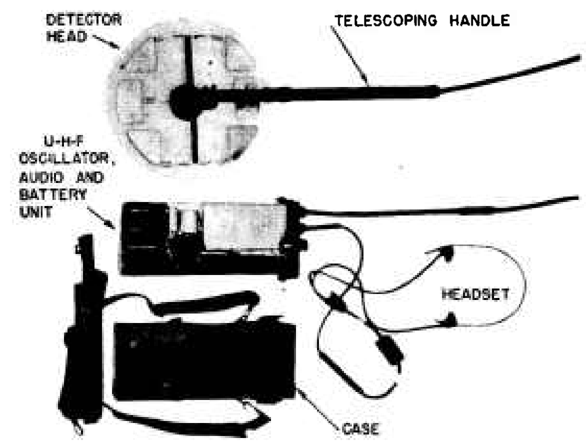


FIGURE 30. AN/PRS-1 (XB-4) detector—set components.

1.5.2 Military Requirements

The basic military characteristics for a combination detector were established by the Engineer Board and the Commanding General, ASF, in March 1945. These specifications include the usual requirements on weight, portability, ruggedness, and watertightness that are standard for all Army mine detectors. The performance desired was equal to or better than that obtainable against a particular enemy mine by the best of the elements used singly. In other words, no loss in performance due to the combination was considered permissible. Another feature was that provision be made for a switch permitting the two sensitive elements to be operated either simultaneously or individually.

1.5.3 Description of Apparatus

The development described in this section was not finished at the cessation of hostilities, with the result that the models described here were rather hastily completed. The principal difference between these and true final models is that the circuit for the metal-detector element does not include phase discriminating features. Thus the circuit as shown would give false indications for permeable rocks and soil.

NONMETAL-DETECTING PORTION OF AN/PRS-6 (XB-6)

Two combination detectors were under development by the same NDRC contractor, the RCA-Victor Division, Indianapolis, Ind.[36] One, the AN/PRS-6 (XB-4), is a combination of the U-H-F detector known as the AN/PRS-1 (XB-2) with a coil system sensitive to metals; and the other, the AN/PRS-6 (XB-6), is a combination of another U-H-F detector, the AN/PRS-1 (XB-4), with a metal-detecting coil array. The two U-H-F detectors (the XB-2 and XB-4) are quite different, but the metal detectors are similar. The XB-2 is more directly an outgrowth of improvements in the original AN/PRS-1. A photograph of this detector set is shown in Figure 29. An important feature of this detector is the placing of the r-f oscillator on the detector head, as in the AN/PRS-1. The XB-4 (shown in Figure 30) utilizes quite a different antenna and receiving array; in addition, it is a so-called transmission-line model with the U-H-F oscillator in the small amplifier pack. A circuit diagram for this in-

strument is given in Figure 31. It is this latter model, the AN/PRS-1 (XB-4), whose modification to a combination detector AN/PRS-6 will be described.

The nonmetal-detecting portion of the AN/PRS-6 is a balanced radiation type of detector. The head of this detector model (see Figure 30) includes three antennas, one for receiving and two for transmitting. The physical size of these antennas has been reduced

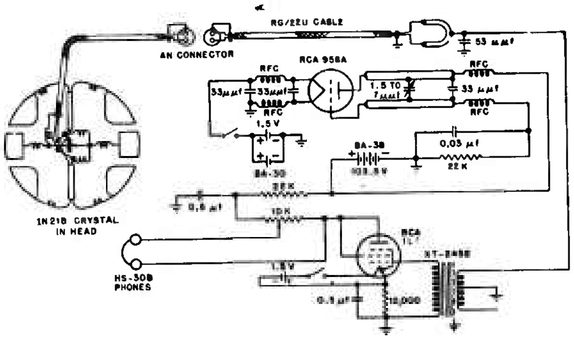


FIGURE 31. AN/PRS-1 (XB-4) detector—schematic diagram.

to a minimum by using both inductive and capacitive loading. The function of the capacity plates is to compensate for variations in the height above ground at which the detector might be operated, thus reducing the sensitivity of the detector to tilt. It was found that tilt sensitivity could be reduced further by putting the antennas in a different plane, the transmitting antennas being mounted against the inside of the top and the receiving antenna near the inside of the bottom of the plastic case surrounding the head.

The outer dipoles (transmitting antennas) are loosely coupled through a Twinax transmission line to a 285-mc oscillator, and the phase of the energy radiated by one is displaced with respect to the other. This displacement is such that it causes a null in the field strength to exist at the position of the center (receiving) antenna. When a mine enters the field of either transmitting antenna, an unbalance occurs at the receiving antenna which is detected by a 1N21B crystal.

As the crystal detector is a device of relatively low impedance (about 50 ohms), a transformer is necessary to take full advantage of the output of the crystal. This, however, caused other serious practical difficulties because a mine signal is of very low frequency (approximately 3 c). The problem was solved by causing the U-H-F oscillator to block at a frequency of about 1,000 c, resulting in 100 per cent modulation of the radiated wave. The modulated 285-mc signal is picked up by the receiving antenna and demodulated by the crystal detector. The resulting audio signal is fed to the 1L4 amplifier over the Twinax cable, which also is used to transmit the U-H-F signal to the radiators. Isolation of the audio signal from the U-H-F signal is effected by the use of r-f chokes and a by-pass capacitor. Both sides of the Twinax line are connected to the receiving antenna through r-f chokes. This arrangement prevents U-H-F leakage from unbalancing the receiving antenna system, since the leakage currents through the two chokes are about 180 degrees out of phase. In the oscillator the center point of the coupling loop is effectively grounded at 285 mc by a 33-μμf capacitor, allowing the audio signal to reach the input transformer free from radio frequencies.

The balanced antenna system utilized in this detector results in two tones being heard when the detector is swept over a mine, one tone coming from each side of the mine as the detector passes over it. When the head is held in the null position between the two tones, it is directly over the mine.

Improvements in Nonmetal-Detecting Portion over AN/PRS-1. The transmission-line unit described above is much superior to the AN/PRS-1 detector in a number of important features: (1) it is insensitive to changes in height above ground, (2) it searches a path about 50 per cent wider than the AN/PRS-1, (3) it gives a more accurate indication of the location of the center of the mine, (4) the weight of the instrument is greatly reduced, and (5) less skill is necessary in operation.

The factors involved in weight reduction were numerous. An important one was the replacement of the type 955 acorn triode of the AN/PRS-1, a tube which requires a 900-mw filament supply, by a 958-A acorn tube, which requires only 125 mw. The use of this tube re-

sulted in further circuit changes; for example, it was found to be impractical to use grid-current variation as an indication of an unbalance of the circuit, because the grid-current variation in the 958-A is inherently greater than in the 955. The substitution of plate-current variation was found to be satisfactory. With reduced battery drain, much smaller batteries could be employed throughout the detector. The above changes resulted in a total weight for the AN/PRS-6 nonmetal-detecting circuit alone of less than 5 lb. The detector head itself weighed only about 2 lb.

The Combination Detector

The combination detector AN/PRS-6 (XB-6) in its final development stage by NDRC is pictured in Figure 32, which shows the mounting of the coils in the U-H-F head. A schematic circuit diagram for this detector set is given in Figure 33. Figure 34 is a photograph of the amplifier and control pack assembly.

The metal-detecting part of the AN/PRS-6 (XB-6) is quite similar to the SCR-625 in circuit detail, although the coil configuration is changed. A push-pull oscillator (see Figure 33), comprising two 1L4 tubes, energizes the large central field coil. The signal picked up by the two receiving coils is fed through a transformer to a two-stage high-gain amplifier with transformer coupling from the last stage to the headset. The U-H-F signal is fed into the screen grid of the amplifier's first stage.

It should be emphasized that the circuit shown in Figure 33 is not in final form, because of the termination of the research program at the close of World War II. If the model had been carried to completion, the metal-detecting circuit would have been augmented by some type of phase discriminating feature, enabling it to reject unwanted signals from permeable ground and other effects previously described.

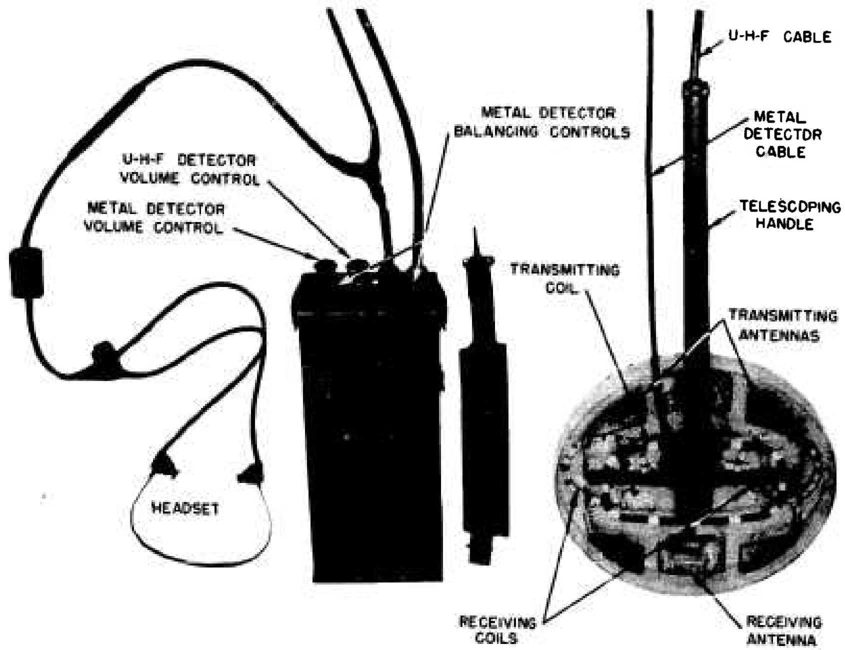


FIGURE 32. AN/PRS-6 (XB-6) detector—set components.

1.5.4 Evaluation of Combination Detector and Universal Detection Program

The utility of the model herein described is that it demonstrates that a metallic search-coil system can be placed in close proximity to the

U-H-F antenna system without reducing appreciably the sensitivity of either component. With the arrangement in the AN/PRS-6 (XB-6), a sensitivity to metals meeting the Engineer Board specification has been obtained.[36] Although forthcoming field trials may reveal that the combination causes reduced sensitivity in the nonmetal-detecting portion, this reduction is not expected to be serious.

phases of the universal detection problem which still remain unsolved: (1) reliable detection of small anti-personnel nonmetallic mines or small mines containing insufficient metal to be detectable by the metal-locating part of the combination, and (2) certain inherent unreliabilities in the performance of the nonmetal-detecting portion. From previous experience it appears certain that the above two objections

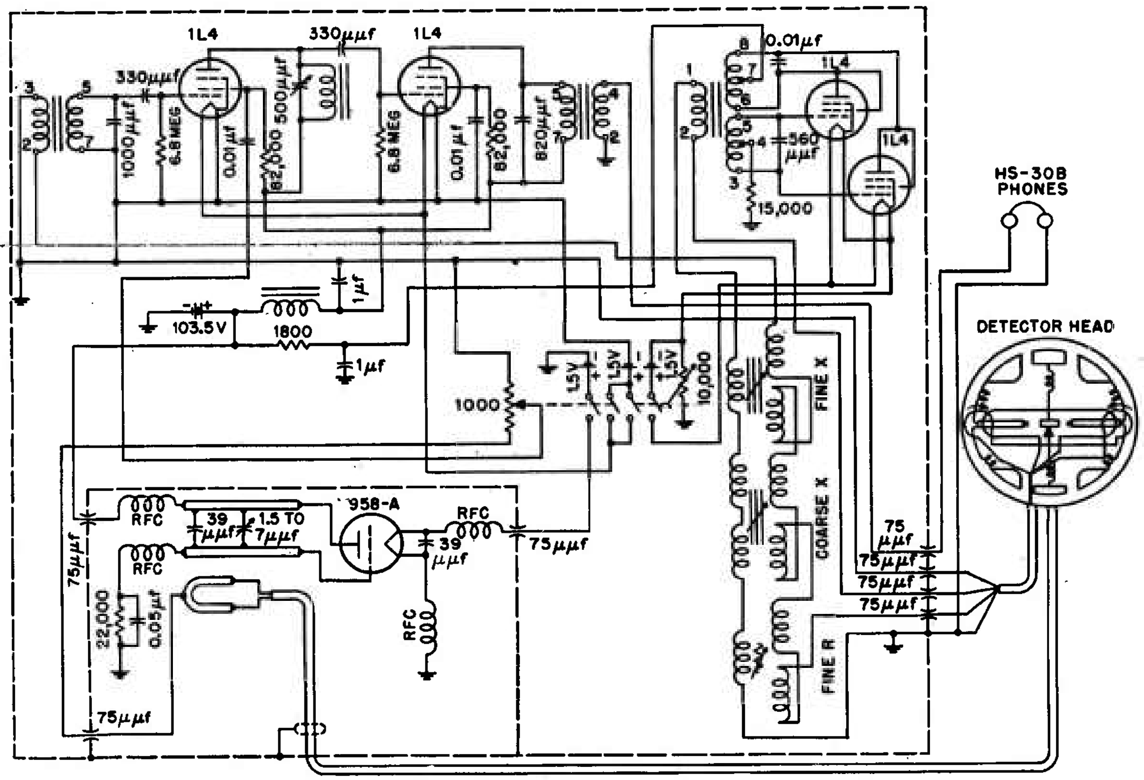


FIGURE 33. AN/PRS-6 (XB-6) detector—schematic diagram.

It is interesting to note that the combination detector is lighter and less bulky than the original model of the AN/PRS-1. At the same time performance has been improved and operation simplified. The addition of the phase discriminating feature in the circuit will increase its weight somewhat, but it seems improbable that this will have unfavorable practical consequences.

The combination detector AN/PRS-6 (XB-6) appears to satisfy the requirements for a universal detector. There are, however, certain

will be present in the AN/PRS-6; it is quite possible that field tests of this combination locator will bring out other objections which may be serious. Until these trials are made, it is difficult to evaluate its performance adequately.

Once it was decided to construct a combination detector from the ground up, the experimental program progressed rapidly and very satisfactorily. It is felt that the work was handled competently and efficiently by the NDRC contractor.

In order to obtain a true universal detector

(one which will detect all mines—large and small, nonmetallic and metallic—in a wide variety of soil conditions), it is apparent that considerable further research work will have to be undertaken. One possibility may be to utilize some variation of a facsimile scheme which will enable the operator to discriminate against stones, roots, and other objects which give indications (at least in U-H-F detectors) identical to buried mines. The Engineer Board has recently (fall 1945) let a contract with a development agency to investigate this method in a long-range program. It is to be hoped that from time to time other ideas will arise which may become the basis for the design of new detectors, and that facilities will be available to reduce these ideas to practice.

1.6 COUNTERMEASURES, ANTI-COUNTER-MEASURES, AND A CONTINUING RESEARCH PROGRAM

1.6.1 Introduction

Land-mine warfare is typical of most combat techniques in that it is not static. Its evolution, however, has been at a slower rate during World War II than many other forms of combat in the sense that specific countermeasure devices, and therefore instruments designed to counter the countermeasures, were never widely used. Countermeasures for standard army mine detectors were developed both in this country and by the Germans (and perhaps by other countries), but no reported instance is known

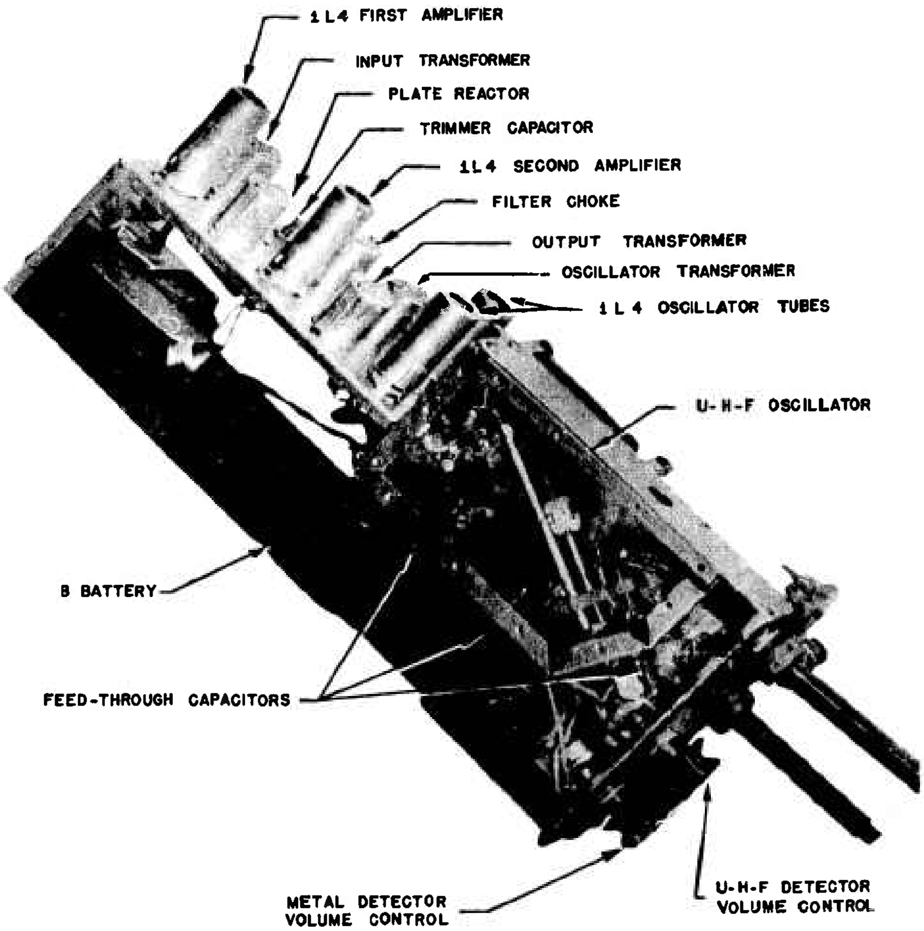


FIGURE 34. AN/PRS-6 (XB-6) amplifier with case removed (U-H-F oscillator section).

of their use against the U. S. Army. Intelligence reports indicate restricted employment of a mine-detector countermeasure against the Russian army and the intended use of this same device against the Allies in the European theater. There has been no report of such an instrument development by Japan or other enemy countries.

Perhaps the major reason for the lack of employment of a countermeasure against the mine detector was that no new development, either in the form of specific instruments or new tactics, seriously weakened the strength of the land mine as a defensive weapon. A minefield containing a high density (say four or five mines per yard of front) of both anti-tank and anti-personnel nonmetallic and metallic mines and covered by supporting fire, both anti-personnel and larger caliber, could not be breached by frontal assault without sizable losses in both men and vehicles at the close of World War II.[e]

It is apparent from the discussion in this report that no detector was capable of locating all known enemy mines reliably. Hand probing with some type of exploring rod comes perhaps the nearest to a solution from the detection viewpoint. This procedure, however, is slow, dangerous, and difficult, and not sufficiently effective to necessitate the employment by the enemy of extensive countermeasures; it is at best an expedient and does not lend itself to rapid break-through of mined positions.

It can be argued, however, that the introduction of mine-detection countermeasures would have increased greatly the difficulty of penetrating minefields, and it can be reasonably assumed that countermeasures and anti-countermeasures will play an important part in the mine warfare of the future.

1.6.2 Countermeasures and Anti-Countermeasures

The German countermeasure against mine detectors was a simple device. It consisted of a mine with an influence fuze sensitive to the field put out by the mine detector. The countermeasure in this case comprised a few turns of wire forming a partially tuned circuit and a sensitive relay (operating on about 20 μa) which was actuated by the induced current in the coil. The tuning in this particular device was sufficiently narrow so that it could be directed only at a single type of enemy mine detector. It could not be operated, for example, both by a U. S. detector (which works at 1,000 c) and by a Russian detector (which uses a frequency of about 3,000 c).

The effectiveness of this countermeasure can be decreased by reducing the field strength developed by the field coil of the detector. This practice, however, decreases the sensitivity of detection. A more adequate anti-countermeasure has been developed by a contractor of the Engineer Board. In this device the field strength of the detector is automatically reduced by the mine signal picked up in the detector. With this circuit it has been possible to detect safely metallic mines fuzed with circuits similar to but more sensitive than the German countermeasure. The overall mine-detection sensitivity of this circuit approaches very nearly that of the best Allied mine detectors.

Undoubtedly, the next step would be to make an influence fuze for a mine which is considerably more sensitive; in a race of this type it is to be expected that the countermeasure (i.e., the mine) will ultimately defeat the detector, since the detector is operating against an inverse-sixth-power law while the fuze (in making use of the field of the detector directly) is functioning on an inverse-cube law. The disadvantage of this scheme from the countermeasure point of view is the need for designing and constructing rather elaborate and delicate fuze mechanisms.

Countermeasures of the above type may be set off or exploded harmlessly by the employment of equipment similar to the ECD. The field established by the energizing system of this instrument could be used to trip the countermeasure before sweeping is undertaken with a standard detector; or alternatively, sweeping could be undertaken more safely with the ECD itself. Equipment designed to detonate re-

[e] For example, see report of Engineer Officer, First Infantry Division, on the employment by that division of land mines in the Battle of the Bulge.

motely booby-traps of the type under consideration could undoubtedly be made to permit sweeping through a rather wide frequency range.

Equipment of the type described above, using a different frequency range, could be made effective against another type of electrical mine fuze. Section T, NDRC, developed during the war a so-called proximity fuze which operated when it approached another object. It was used in an influence mine which is a mine-detector countermeasure. This mine is sensitive to the presence of a foreign body near the fuze; hence, it would be a countermeasure against any mine detector, irrespective of whether an exploring electromagnetic field is associated with it or not.

A third device which may be considered a countermeasure is a mine fitted with a mechanical tilt igniter. Such an igniter was developed by the Germans during World War II. The mine is exploded when the mine detector head sweeps against the rod part of the tilt igniter, which extends 6 in. or more above the surface of the ground. This device would probably be most effective at night, when it would be impossible to see a well-camouflaged tilt rod. The wide-scale employment of this as a countermeasure would necessitate, if nothing else, a rather complete change in standard operating procedures with mine detectors; conceivably, it might also demand certain design changes in mine detectors. The device would be particularly troublesome if it could be made of completely nonmetallic materials.

Small trip wires connected between mines may also be considered as a countermeasure against mine detectors. To overcome this obstacle, a small trip-wire detector, which can be attached to a regular detector, has been developed, but not placed in use. It is anticipated that the trip-wire detector would be fairly satisfactory as an anti-countermeasure.

From the general countermeasure point of view, one of the most satisfactory devices would be simply the development of low-pressure-functioning mines which could not be detected by enemy mine detectors. Small, nonmetallic anti-personnel mines are now in this category.

1.6.3 A Continuing Research Program

The failure to prosecute a peacetime program for the development of new mines, mine detectors, and countermeasures can result in serious consequences. This statement is based on the assumption that it will be necessary in the future to occupy physically territories held by an enemy. In such an operation it is reasonable to expect that mines and booby-traps will be encountered, perhaps in very large numbers. Under these circumstances the possibility of a single enemy countermeasure rendering all U. S. mine detectors useless can best be guarded against by a thorough and efficient mine warfare research and development program.

The objectives of such a program can be stated clearly. From the long-range point of view the purpose is the development of a detector capable of locating with 100 per cent reliability all types of land mines and booby-traps. This detector should be, so far as possible, impervious to countermeasure technique. To anticipate possible countermeasures by the enemy, and to permit the use of mines in offense by friendly forces, work should be continued actively on the development of countermeasures to mine detectors (as well as to other methods of clearing minefields). This program, which is still not well established, might include not only countermeasures in the normal sense of an influence-type electric fuze, but also the development of mines which cannot be detected by standard mine-detector practice.

From a more immediate viewpoint, research should be continued to develop a locator of small nonmetallic anti-personnel mines and nonmetallic anti-tank mines which will be reliable for all soil conditions. It appears that the successful conclusion of this project will not come from simple engineering advances in mine-detection techniques now being investigated; it is believed that a satisfactory solution to this problem will come only from the application of some new and perhaps as yet unknown technique. This is one way of stating that considerable fundamental research must be undertaken to solve this problem adequately.

Again, from the short-range point of view,

the development of detectors which are not particularly susceptible to countermeasure techniques is in its infancy. It is to be expected that continuing engineering advances, both in the development of countermeasures and of non-countermeasurable detectors, will result in important practical advances. In other words, there does not exist the same preponderant need for fundamental research in these fields that there is in the detector field, as research of a less fundamental nature can still give very useful results.

Chapter 2

MECHANICAL AND DEMOLITION CLEARANCE OF LAND MINES

By *John S. Hornbeck*

2.1 INTRODUCTION

The purpose of this report is to summarize the technical program prosecuted by Section 17.1, Instruments, on mechanical and demolition methods of clearing land minefields.

The report is organized into three divisions: a summary, mechanical clearance, and demolition clearance. No attempt is made to report in detail the theoretical and experimental investigations undertaken; these may be found elsewhere. Rather it is intended to present sufficient material to indicate the scope of the work undertaken and the useful results accruing therefrom. Attention is directed to the incomplete solution as yet obtained to the land-mine problem.

The Service control numbers or projects under which the work herein reported was conducted were CE-32 and OD-133. The former was a general request from the Corps of Engineers for assistance in all phases of land-mine clearance, and the latter was restricted to mechanical clearing methods.

2.2 SUMMARY

The advent of the land mine as an effective combat weapon in World War II was responsible for an intensive research and development program to discover means of counteracting it. The first and perhaps easiest step in this direction was the design and production of metallic mine detectors. Mechanical and demolition methods of clearing minefields were also investigated at an early date, but it proved to be more difficult to find in these fields devices which were as satisfactory as a simple metallic mine locator.

From a tactical point of view the appeal of mechanical and demolition methods is the speed with which a lane through a minefield can be cleared. In detector operations many hours must be spent, frequently at night, locating mines and removing them or detonating them harmlessly in place. Often these operations give advance notice to the enemy of an imminent attack. If explosives could be placed on a minefield in a time interval of a few minutes at most, breaching of the field could be achieved quickly, permitting motorized troops an element of surprise in an attack. Thus, given the method of accurately placing a sufficient explosive charge, the armor commander has a powerful weapon at his disposal. Similarly, if enemy fire over a minefield was neutralized, a suitably designed mechanical mine exploder could precede tracked vehicles, clearing a path for them as they advance. Mechanical mine exploders would also be quite useful for keeping roadways open and clearing rear areas where for some reason it was undesirable to attempt to locate the mines individually.

2.2.1 Military Requirements

American military requirements for mechanical mine exploders are in general quite similar to requirements for all combat weapons. The device must be capable of doing its assigned task efficiently. It must be rugged and easy to transport, either under its own power or by other means. More specifically, Army Ordnance desired a mechanical mine exploder which would detonate commonly used enemy mines at operational depths of burial (say up to 6 in.). Preferably the exploder, if mounted on a tank, should not require an auxiliary power source, and the exploder plus tank must be easily maneuverable under combat conditions. These would include unloading the vehicle from amphibious landing craft and the negotiation of extremely muddy roads and land areas. Army Ordnance also emphasized the desirability of obtaining an indestructible mechanical clearing device. (This was usually in conflict with the maneuverability requirement.) Sufficient ground coverage is necessary so that the exploder does not occasionally miss mines. It is also desirable for the mine exploder to be capa-

ble of returning enemy fire while in the process of carrying out its assignment.

With regard to explosive clearance, Army Ground Forces required a safe, accurate means of placing an explosive charge, the equipment associated with the device to be packaged in a form readily transportable, the total weight of the device to be as low as possible, and its operation to be practically foolproof. Time of assembly behind the front lines, if necessary, is also an important consideration, as is the time required for the device to be placed in the desired position on the minefield.

2.2.2 Scope of Work

In the mechanical clearing domain two projects were undertaken by NDRC. One dealt with the development of a heavy, self-propelled, remotely controlled roller device, which could be operated from a tank or other suitable station and maneuvered through a minefield. The second comprised design studies of a flail-type mine exploder known as the Rotaflail and the building of models. This latter project was the only one of the two which appears to be particularly promising and therefore attention is restricted to it. NDRC development work on the Rotaflail comprised: (1) development of the Rotaflail principle and a mathematical analysis of it,[a] (2) model studies of the Rotaflail principle and resulting design conclusions,[b] and (3) consultation and cooperation with Army Ordnance on the design and testing of larger Rotaflail models.[c]

In the demolition phase of the problem, Section 17.1 activity was confined mainly to the development of techniques and methods for evaluating demolition clearance devices. This included development, calibration, and application of indicator mines and a general study of the blast properties of anti-tank mines. Consulting aid and design work also contributed to a few of the Engineer Board mine-clearance design projects.

[a] Mathematics Panel.
[b] By Section 17.1.
[c] By Section 17.1.

2.2.3 Technical Accomplishments

In this section a brief summary is given of the useful results obtained from the Section 17.1 program.

THE ROTAFLAIL AND ITS MODIFICATIONS

The Rotaflail consists of a large rotating drum, mounted in front of a tank, carrying flails which beat the ground. The bottom of the drum is close to the ground so that at the instant of impact with the ground the flails are substantially horizontal and moving vertically. Model studies were completed on the motion of the rotational system leading to conclusions on optimum design characteristics. The magnitude and distribution of the impact forces on the ground with particular reference to their efficiency in detonating land mines were also investigated. This work resulted in the following conclusions: (1) since there is a wide spread in the energy absorbed by individual mines under impact of a flail, generous factors of safety must be introduced to make sure that mines are not left undetonated; (2) when a Rotaflail with a 3-ft drum is used against TMi-43 indicator mines buried 4 in. deep, a drum rotational speed of approximately 125 rpm is desirable; this leads to a calculated power dissipation of 220 hp by 21 flails; (3) effectiveness in mine clearing decreases with increasing clearance between the bottom of the drum and the ground, although this is not critical; (4) a Rotaflail operating at the above drum speed is considerably more effective than a tank tread in detonating mines; (5) an 8-ft flail is effective to a distance of 5 or 6 ft from the tip of the flail, and this decreases directly with drum diameter; (6) studies of a self-rotating Rotaflail ("lawn mower"), as contrasted to a Rotaflail driven by a power take-off from the main tank motors, indicate that it is not so satisfactory as the independently driven type.

In addition to studies of the Rotaflail principle, investigations were undertaken of a slightly different type of device known as the Springflail. The Springflail, suggested by the Ordnance Department, ASF, eliminates the need for a large drum in front of the driving

tank by mounting the flails on resilient arms (flat springs) which project from a small rotated axle. The axle can be close to the ground; the springflails flex as they pass under the axle along the ground. The springs and flails then straighten out radially as they travel around for the next impact because of centrifugal forces on the flails and the tendency of the springs to straighten. When these conditions are satisfied, the flails again are substantially horizontal and moving vertically at impact. Model studies of the Springflail have led to the conclusion that it should be a workable device; a full-size model might easily be superior to the Rotaflail. It was recognized, however, that the Springflail is a more complicated device; there are more variables in its design and its operation is somewhat more critical. The advantages offered by the Springflail appear to be: (1) less weight, (2) less obstruction to the vision of the operator, (3) less target area presented to gunfire and mine blasts, and (4) higher rotational and forward speeds.

Investigation was also made of a second modification of the Rotaflail comprising the use of rigid extensions on the drum with the flail chains connected to the extremities of the extensions. It was thought that this technique might make possible a reduction in drum diameter. Tests of a model indicated that if such a modification should operate satisfactorily, it would most likely be critical to speed, flail length, and weight under normal conditions.

Indicator Mine Developments

In order to evaluate the effectiveness of a minefield-clearing device of the shock impulse type, a method must be found for accumulating sufficient data to obtain the probabilities of detonating various types of mines buried under a variety of conditions. One method developed to secure these data is to measure some quantity characteristic of the reaction of the mine to shock impulse, using an indicator mine of such type that the probabilities of detonating various types of enemy mines can be computed from the indicator mine data. Two instruments of this type, the TMi-43 indicator mine and the universal indicator mine, were developed by Section 17.1. In order to extend the range of the original universal indicator mine (M1) to include more "blast-proof" mines, an M2 modification was also designed. Various known enemy mines were calibrated against the indicator mines, permitting data accumulated with them to be interpreted in comparison with other mines under the same experimental conditions. The indicator mine developments proved to be powerful factors in increasing the reliability of results and markedly decreasing the amount of work required to evaluate minefield clearance devices.

Extensive measurements of the dynamic characteristics of enemy anti-tank mines were carried out in the course of the indicator mine program. These measurements established experimentally the basis for an indicator mine, namely, that the condition for detonating a shear-pin type mine can be expressed in terms of the total energy absorbed by the mine, a quantity which is substantially independent of the nature of the impulse. Detailed studies of anti-tank mine characteristics also made possible the expeditious design of replica models of enemy mines. In some instances these replicas were used in the field only until the mines had been calibrated in terms of the universal indicator mine; while in other cases, when examination showed that the principle of operation of an enemy mine was substantially different from that of the universal mine, the replica mines had to be planted in addition to indicator mines. (Usually a sufficient number of enemy mines were not available for demolition tests to be carried out directly with them.)

The Effect of Point Charges on Anti-Tank Mines

In conducting the program for the calibration of the universal indicator mine, a large number of tests were made using demolition point charges.[d] The data obtained from these tests have been analyzed and an empirical formula devised which allows the behavior of the universal mines to be predicted for a wide variety of test conditions. In addition, a method has been worked out whereby this formula can be applied to a number of foreign mines, usually

[d] In much of this work Division 2, NDRC, gave invaluable assistance.

of the shear-pin type (e.g., TMi-43, Dutch Mushroom Top, Japanese Yardstick, and French Light Anti-Tank). Some success was realized in correlating indicator mine data with mines differently fuzed (e.g., Japanese J-13 and J-16 anti-boat mines). Probabilities of detonation can be found for the indicator mine and mines related to it under the action of bare (uncased) point charges and other types of point charge whose action can be expressed in terms of an equivalent charge weight of cast TNT. A further result is that data obtained with a universal indicator mine can be used to determine how variations in ground conditions and method of burial affect the probability of detonation.

SHOCK TUBE

A shock tube[e] was constructed and calibrated which permits the study of dynamic characteristics of anti-tank mines under highly controlled conditions. By using the shock tube, variations in ground conditions which are extremely difficult to control in the field are practically eliminated, and a more uniform, repeatable shock wave can be produced. The present tube is limited to peak pressures in the shock wave of less than 150 psi.

2.2.4 Evaluation

ROTAFLAIL AND SPRINGFLAIL

Model studies of two types of flail mine exploders have been completed and full-scale tests made on a prototype model of one of these, the Rotaflail, in cooperation with the Ordnance Department. No data resulting from the evaluation studies of the Rotaflail indicate that a workable device cannot be made. The inference is, rather, that the basic principle is sound and that the design and construction of true prototype models is simply a matter of straightforward engineering. At the cessation of hostilities two Rotaflail prototype models were under construction by the Ordnance Department. The investigation of the Springflail, while incomplete, seemed to indicate that this design principle is promising and could lead to the construction of a mechanical clearing device superior to the Rotaflail.

The Rotaflail and Springflail principles both appear to have advantages over other types of flail exploders, such as the British Scorpion; and it is recognized that on the basis of combat usage the British flail exploders have been far superior to disk roller and other similar exploders developed in this country. In the Rotaflail and Springflail an extended length of flail comes in contact with the ground ahead of the drum, whereas in the Scorpion only the tip of the flail strikes the ground at a point almost directly below the rotating drum. One is a beating action, the other a digging action. This difference accounts for these apparent advantages of the Rotaflail type: (1) less damage is likely to be inflicted to the drum if the explosion of a detonated mine occurs in front of rather than under the drum; (2) there is less probability of dirt and unexploded mines being thrown back on the pushing tank with the beater-type action; (3) the beating action is more efficient in detonating buried mines because the impulse is delivered vertically. The principal disadvantage of the Rotaflail is its requirement of a larger drum; a 5-ft diameter would be ideal for flailing action, but such a large diameter restricts the visibility of the tank driver. A compromise to a 3-ft diameter has been made in the models being constructed by Ordnance at the time of writing, the model studies indicating that this should give satisfactory flail performance. The Springflail does not have this same drum-diameter limitation.

The experimental investigation carried out by the Section 17.1 contractor[f] appears to have been completed efficiently and soundly. However, since the investigation was initiated in the fall of 1943, the question may be raised appropriately as to why, in view of the promising results, the development as a whole did not come nearer to actual combat use. This may be ascribed directly to delays on the part of the Ordnance Department, ASF, for which no satisfactory explanation is available. In any case, their efforts were concentrated on heavy rollers, and the promising results obtained with the

[e] Developed from models originated by and designed with the cooperation of Division 2, NDRC.

[f] Carnegie Institute of Technology, Pittsburgh, Pa.

Rotaflail model were ignored until the information was brought to the attention of Headquarters, ASF. A directive was issued, and a belated effort was made to build models in compliance therewith.

It should be noted that all known mechanical

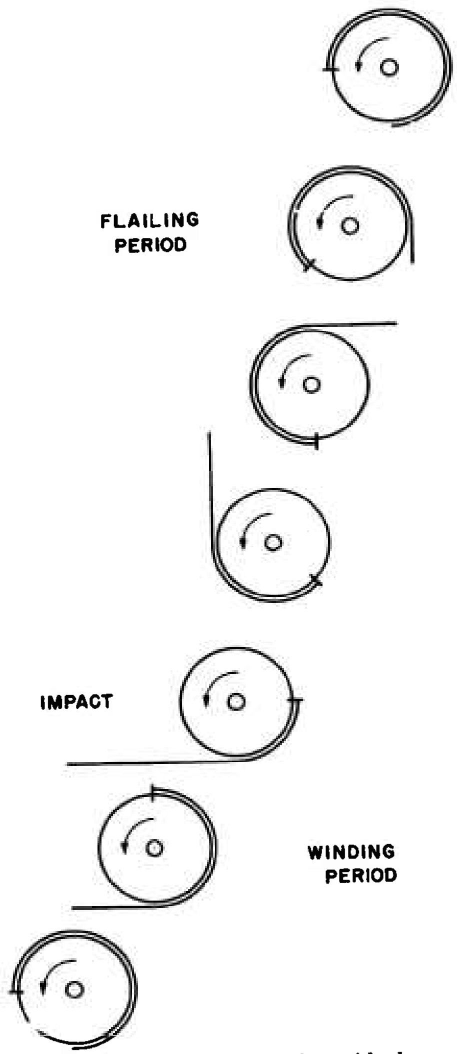


FIGURE 1. Theoretical action—ideal case.

mine-clearing devices have limitations which may restrict their future use operationally. Countermeasures for this equipment were developed by the Germans and placed in use. The simple expedient of occasionally planting land mines containing large explosive charges (for example, 200 lb) would make the advisability of employing mechanical mine exploders extremely doubtful. This was in fact the situation in the Japanese theaters as the Japanese planted many charges considerably larger than that contained in an ordinary anti-tank mine (approximately 10 lb). Although the flail-type mine exploders are believed to be the most promising mechanical type under development, it is therefore questionable whether they offer much hope as a solution to the land-mine problem. They were, however, cheaper than tanks and could have been extremely useful even though an occasional unit was lost as a result of enemy countermeasures.

ANTI-TANK MINE STUDIES AND THE INDICATOR MINE

The development and application of indicator mines to the evaluation of explosive mine-clearing devices is believed to be a major accomplishment. The indicator mine has proved to be much more useful than was initially expected. Without this device and the associated information obtained with it, it would have been virtually impossible for the Army to conduct an extensive demolition clearing program.

The auxiliary technique of the shock tube is one which appears to be exceedingly promising and one which has not been applied extensively. Studies with it to date establish it as a powerful and useful tool for investigating demolition clearance of anti-tank mines and analyzing their characteristics.

The efficient and timely conduct of these phases of the program was in a large measure due to the ability and resourcefulness of the Section 17.1 contractor.[g]

2.3 FLAIL-TYPE MECHANICAL MINE EXPLODERS

In this chapter experimental investigations of the Rotaflail, its various modifications, and the Springflail are discussed in greater detail. The comparative advantages of a self-rotating Rotaflail and a Rotaflail independently driven by a power take-off are considered, as are the

[g] Gulf Research and Development Company, Pittsburgh, Pa.

advantages and limitations of wholly flexible flails and flails connected to rigid extensions from the central rotating drum.

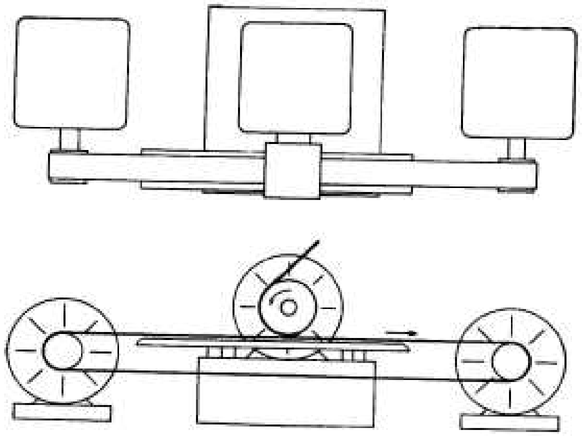


FIGURE 2. Arrangement of apparatus.

2.3.1 The Rotaflail

The Rotaflail consists of a large drum carrying chains or cables which act as flails, the behavior of which is illustrated in Figure 1. The drum is turned and at the same time moved forward at such a speed that the bottom of the drum has a small forward velocity with respect to the ground. This type of flail action was first suggested by Brown University and is developed in a report of the Applied Mathematics Panel. It will be noted that at the instant of impact, when the bottom of the drum is close to the ground (see Figure 1), the flails are nearly horizontal and moving vertically. This action is quite different from that of flail-type mine exploders previously constructed in this country and in Britain. In these a much smaller drum is utilized, with a correspondingly larger clearance between the bottom point of the drum and the ground. In these devices the flails at the moment of impact are substantially vertical and moving horizontally. Thus only the tips of the flails are effective on buried mines by a digging action.

The advantages visualized for the Rotaflail principle and therefore responsible for the investigation were: (1) detonation of the mine in front of rather than under the flail drum; (2) a decreased tendency to throw dirt and mines back on to the pushing tank; and (3) a more efficient and effective transmission of kinetic energy from flail to buried mines.

Initial model studies of the Rotaflail were made to substantiate experimentally the conclusions of the mathematical analysis and to investigate further the practicability of the idea. Early tests were conducted to analyze how the trajectories depend upon the type of flail, the rotational speed of the drum, the speed of translation, and the clearance between drum and ground. A schematic diagram of the ap-

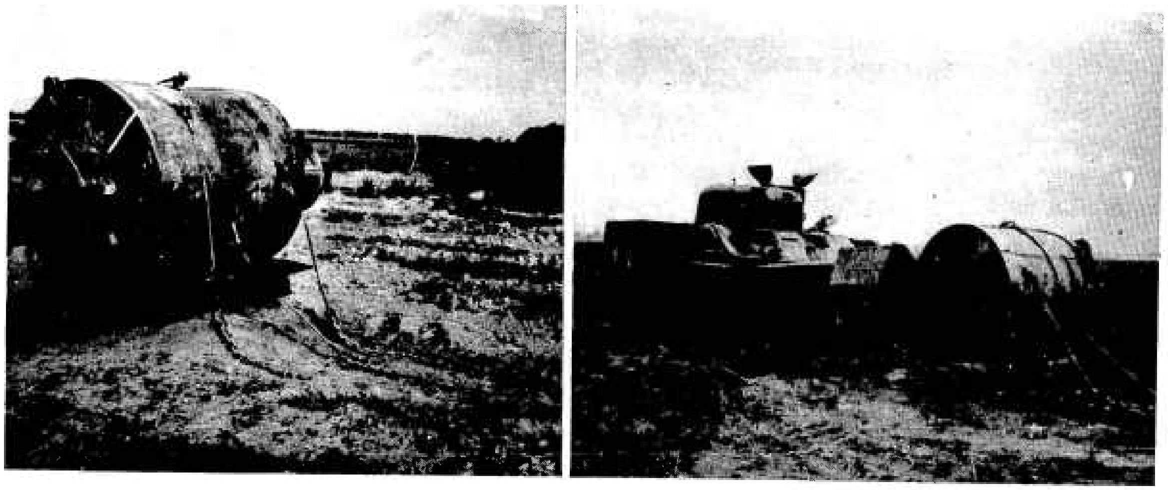


FIGURE 3. Partial full-scale Rotaflail (*left*) with chain flails and (*right*) with loaded rope flails.

paratus utilized in this work is shown in Figure 2. The axle of the drum to which the flail is attached does not move and the ground is simulated by a moving belt. The drum of the model was 10.72 in. in diameter.

The results of the first model tests,[2] which were completed in December 1943, were sufficiently promising to enlist the cooperation of the Ordnance Department in conducting field tests with a partial full-scale model. This series of tests[3] was conducted in August 1944 at Aberdeen Proving Ground with the model shown in Figure 3, and good results were obtained, as indicated by the conclusions drawn.

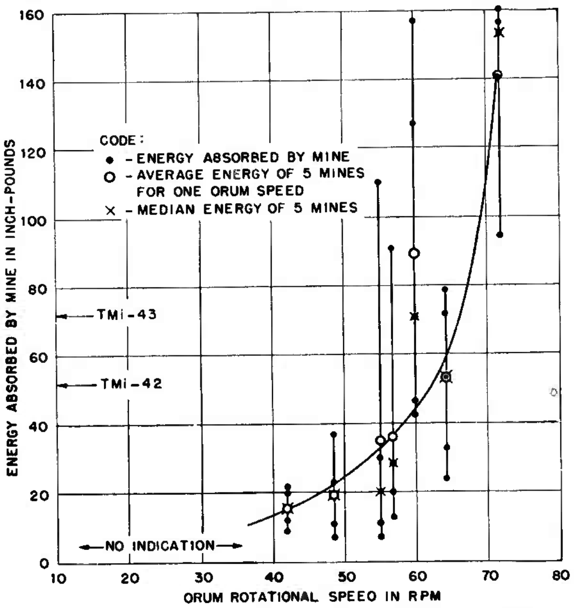


FIGURE 4. Energy absorbed by indicator mine buried 5 in. vs drum rotational speed. Drum 6 in. above ground.

Flailing Action

The instantaneous shapes and motions of the flails of the partial full-scale model were found to be in good agreement with those of the small-scale models and these, though showing some irregularities, were satisfactory.

Strength of Impact

A sufficient impulse was found to be delivered by the Army standard chain flail to detonate a German Tellermine (TMi-43) buried 10 in.

Active Length of Flail

Slightly more than half the extended length of the flail on the ground was effective in detonating anti-tank mines.

Effect of Explosion on Partial Full-Scale Model Rotaflail

A standard M1A2 high-explosive anti-tank mine detonated by the full-scale Rotaflail had but little effect on the drum, flails, tank, or tank personnel.

After these test results were reported, the Commanding General, ASF, directed the Chief of Ordnance to construct two full-scale models of the Rotaflail. The Ordnance Department requested NDRC to make further studies and asked for cooperation in other tests with the partial full-scale model at Aberdeen. Consequently a second series of tests[4] was held at Aberdeen in May 1945. In these tests particular attention was paid to power requirements for operating the flail and other possible design limitations.

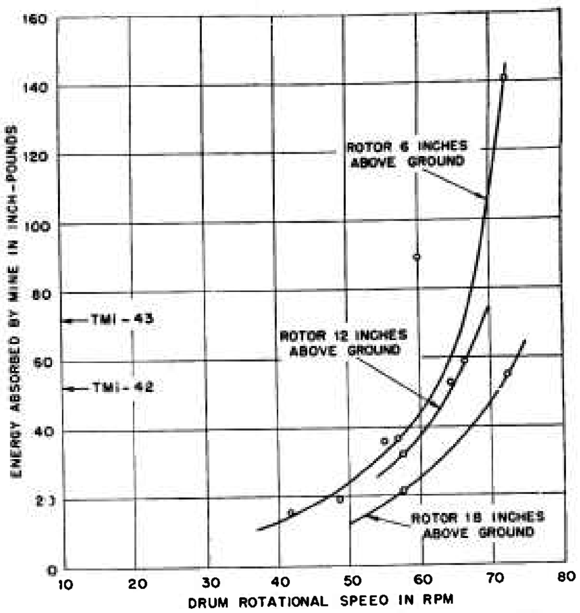


FIGURE 5. Energy absorbed by indicator mine (average of 5 mines) vs drum rotational speed for various drum-ground clearances.

Energy Absorbed by Mines

A wide variation was found in the total energy absorbed by buried mines under action

of a flail, as indicated in Figure 4. With this wide variation in energy, which can be explained by a number of suppositions, generous factors of safety must be introduced, especially if averages are used, to make sure that mines are not left undetonated.

Effective Drum Speed

The present tests indicate that with TMi-43 mines buried 5 in. deep and using a Rotaflail

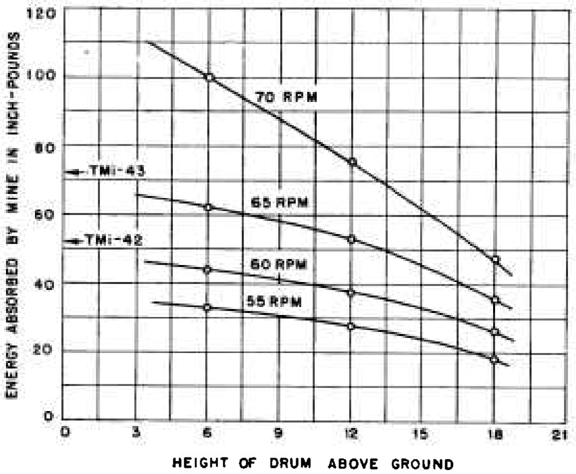


Figure 6. Energy absorbed by indicator mine (average of 5 mines) vs drum-ground clearance for various drum rotational speeds. Drum diameter—5 ft. Mines buried 5 in.

with 5-ft drum diameter 6 in. above the ground, a speed of 70 rpm would be desirable; at 7-in. burial depth—75 rpm; and at 10-in.—80 to 85 rpm. With a larger clearance between the drum and ground, the speed should be increased.

Effective Clearance

The relationship between the energy absorbed by mines at a depth of 5 in. and drum clearance is shown in Figures 5 and 6. (The validity of these curves is open to question because the data are not sufficiently numerous; however, the direction of change is reasonably certain.) From these figures it is readily concluded that the drum should be operated as close to the ground as possible.

Effect of Mine Depth

Figure 7 shows how the effectiveness at different speeds varies with the depth at which the mines are buried. At 75 rpm, for example, TMi-43's at 5 and 7 in. would be detonated, but perhaps only half of those at 10 in. (It should be noted here that these depths of burial are considerably in excess of those obtained with other types of mechanical mine exploders.) The tests further indicated that a Rotaflail turned at the speeds mentioned is considerably more effective than tank treads in detonating buried mines. This is particularly true if the ratio of drum rotational speed to translational motion of the tank is chosen such that a buried mine has a high probability of being hit more than once.

Recommendations Concerning Design of Prototype Mine Exploder

On the basis of field and laboratory tests a number of conclusions have been drawn rela-

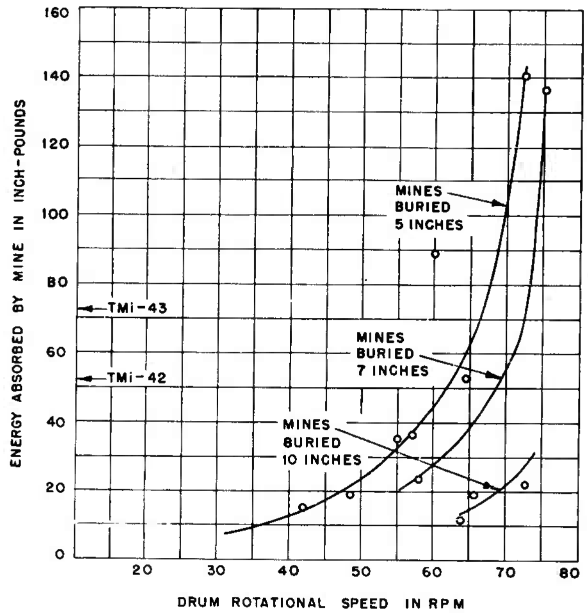


Figure 7. Energy absorbed by indicator mine (average of 5 mines) vs drum rotational speed for various depths of mine burial. Drum-ground clearance—6 in.

tive to the construction of a first prototype model.

1. A Rotaflail with a 3-ft diameter drum of width equal to the overall driving tank should be constructed. (The choice of 3 ft for the diameter is a compromise with visibility—the

larger the diameter the poorer the visibility for the tank driver and the better the flail action.)

2. The flails should be half wire cable and half chain, should weigh 7 lb per ft, and should be 5 ft long. The flails should be spaced in planes no more than 6 in. apart.

3. The drum should be rotated at 125 rpm, for which the calculated power into the 21 flails is 220 hp. This speed should be adequate for clearing TMi-43 mines 7 in. below the surface of the ground.

4. The clearance of the drum above the ground should be as small as practicable—about 6 in.

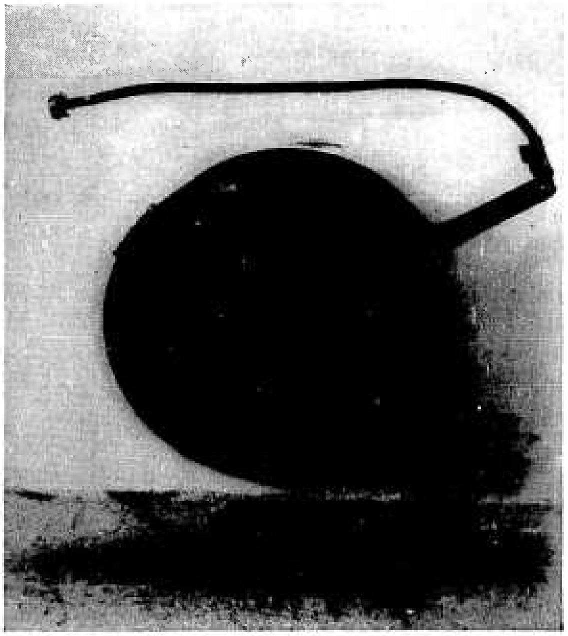


FIGURE 8. Rotaflail model with rigid extension.

THE SELF-ROTATING ROTAFLAIL

The above discussion applies to Rotaflails independently driven by either a power take-off from the main tank engine or from an auxiliary engine. Consideration has been given to a mechanically simpler type of flail in which the drum is rotated merely by being in contact with and pushed along the ground. This simplification would make unnecessary an extra engine, transmission, and long drive shaft to power the drum.

The study of the self-rotating Rotaflail indicated that although it may be mechanically simpler, it has inherent disadvantages,[3] namely: (1) the forward velocity must not fall below a critical value, which for the dimensions and flails considered is about 16 mph; (2) at least four flails must be spaced around the periphery of the drum to get adequate coverage along any line of advance; (3) the power required to turn the drum would then be four times that required for the separately driven Rotaflail (however, it should be noted that the ground would be covered four times as fast); (4) difficulty might be expected in supplying the power through the ordinary traction between drum and ground; (5) irregularities in the level of the ground would tend to make the drum bounce, further aggravating the traction difficulties.

THE USE OF RIGID EXTENSIONS

A possible method of obtaining a better compromise between the use of a small drum for good vision and long flails for keeping the explosions remote from the drum is to mount rigid extensions on the drum at the end of which the flails are attached. A small-scale model of such a flail is shown in Figure 8. In the laboratory model shown, the relative size of the extension was such that a prototype might utilize a 3-ft drum and have flails mounted on 12-in. extensions. The laboratory

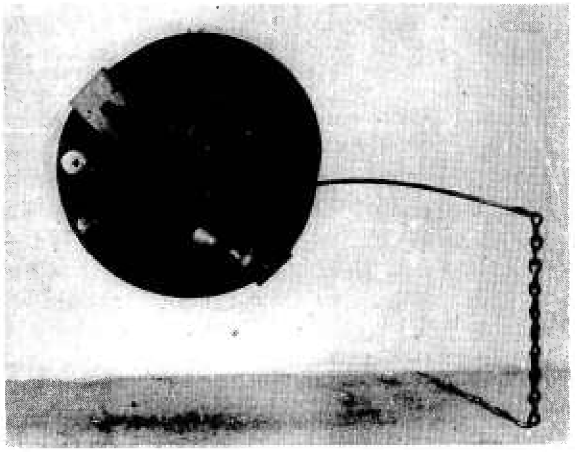


FIGURE 9. Laboratory model of Springflail.

model was found to operate unsatisfactorily except at certain critical speeds, flail lengths, and weights. It was concluded, therefore, that the effectiveness of flails designed with rigid extensions might be seriously reduced in operation if the flail ends were blown off or if mud stuck to the flails and changed their linear density. Furthermore, little usable length of flail is gained by the procedure.

2.3.2 The Springflail[4]

The Springflail laboratory model shown in Figure 9 consists of a 10-in. chain flail attached to a 2.5-in. rotating hub with a 12-in. flat spring able to flex in the plane of rotation. The spring is made up of several leaves which are adjustable in length. The ends of the leaves are loosely strapped together and to the center leaf so that the spring is an integral unit, but the leaves can slide independently as it bends. In use the hub is mounted close to the plane of impact so that the spring must bend after each impact. The hub on the model can be offset and oriented with respect to the regular axis of rotation, allowing the testing of a partly rigid and partly resilient flail support arm for the simulation of springs mounted at an angle (but within the plane of rotation) on a rotating crank. This latter mode of operation appeared to offer possibilities in the reduction of spring stresses without sacrificing effectiveness.

The Springflail, although the studies are incomplete, appears to be a workable type of mine detonator. Tests of the model suggest the possibility that its effectiveness may be made equal to that of the Rotaflail, and it would offer some advantages, such as less weight, less obstruction to the vision of the operator, less target area to counterfire, and higher rotational and forward speeds. The higher forward speed is due to the lower relative angular velocity between the flail and the hub. On the Rotaflail the angular velocity of the flail, while it is unwinding, is twice that of the drum,[1] but it is somewhat less than twice the hub speed on the Springflail the instant before impact. Thus, to obtain similar flail kinetic energies the hub speed of the Springflail must be greater than the drum speed of the corresponding Rotaflail. A greater impact repetition rate and a higher possible forward velocity result.

The model studies also brought out some inherent disadvantages in the Springflail. The springs scraped the ground as they flexed back under the hub; they would probably throw dirt back on a driving tank. It is believed that the Rotaflail is easier to construct and that it would probably be more durable. There is no drum surface present on the Springflail to control the bouncing of the flail after impact; without this control on the model the chain bounces back on itself into a small pile.

2.3.3 Conclusion

A flail-type mine exploder, as exemplified by the Rotaflail and possibly the Springflail, is believed to be the closest approach to a satisfactory solution in terms of mechanical clearance. This view is concurred in by officers in the Corps of Engineers and Army Ground Forces and may be found expressed in the minutes of a combined Service meeting called by the Office, Chief of Engineers in May 1945 to review all mine-detection and mine-clearing developments. The advantages of the flail-type over disk-roller and other mechanical mine exploders are briefly: (1) its lesser weight permits greatly increased mobility, (2) the Rotaflail can be expected to detonate mines planted at larger burial depths, and (3) it can probably be produced more easily and cheaply.

It is believed, however, that like all mechanical mine exploders the flail-type is limited in application. The device is readily countermeasured; the expedient of planting an oversize charge sufficient to demolish the exploder would probably negate its use if such charges were encountered very often. The Germans developed a countermeasure to mechanical exploders which is quite simple and effective and does not require as much explosive charge: they planted a fuze-actuating mechanism some 8 to 10 ft in front of the main explosive charge; when the flail or exploder disk actuates the fuze, the main charge blows up under the driving tank. An additional countermeasure in case

of flail-type mine exploders would be the design and planting of mines having large mechanical damping constants so that the quick impact of the flail is not of sufficient duration to explode the mine.

It is not to be concluded, however, that the above limitations should preclude the completion of the flail mine exploder developments. The effectiveness of countermeasures depends to a very large extent on how ably they are employed by the enemy. There is no guarantee —in fact there is reason to believe otherwise— that the enemy will not be proficient in employing countermeasures at the outset of another war. A stronger argument for completing the developments is simply that the flail-type exploders appear to be the most promising of any known type of mechanical mine-exploding equipment, and therefore should be completed as representative of the best in a category. It is also possible that future development work will result in uncovering means of reducing the effectiveness of countermeasures.

2.4 DEMOLITION CLEARANCE TECHNIQUES

2.4.1 Introduction

The Engineer Board, Fort Belvoir, Virginia, and the JANET Board, Fort Pierce, Florida, were the agencies in this country principally responsible for the development of equipment for clearing lanes through minefields by demolition methods. A description of the specific development projects may be found in published reports of these boards.[14] Section 17.1 was able to contribute to a minor extent to the design of certain of this equipment, but its major contribution was the development of techniques for evaluating demolition clearing devices and the analysis of the effects of demolition charges on anti-tank mines.

In evaluating demolition devices the problem fundamentally is to determine the effect of shock impulses on anti-tank mines, or more specifically, to determine the probability of detonating various enemy mines as a function of distance from explosive charges. At the outset it is apparent that this problem involved a large number of variables, some very difficult to control; to enumerate a few—type of mine, depth of burial, soil conditions, atmospheric conditions, distance from explosion, explosive charge weight, casing, charge form (point or linear), and type of explosive. The development of methods and techniques for handling these variables is described and a brief description is given of Section 17.1 contributions to the design of demolition clearing equipment.

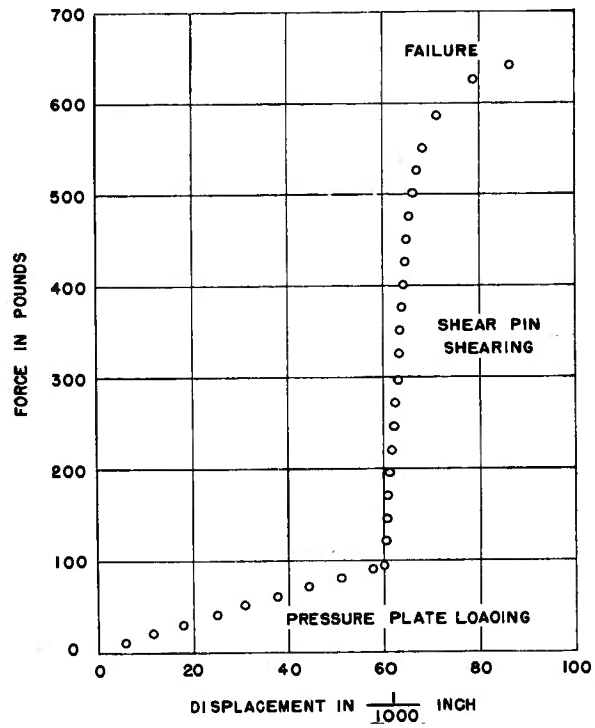


FIGURE 10. Force-displacement characteristic for Type TMi-43 anti-tank land mine (steel shear pin).

METHOD OF ATTACK

The general method of attack followed in this development may be summarized briefly: (1) a study of the static and dynamic characteristics of various types of anti-tank mines when subjected to shock impulses in order to determine which mine characteristic is least dependent on the type of impulse; (2) the design and calibration of indicator mines to

measure this characteristic; (3) a determination of the effect of shock impulse from point charges on an indicator mine, and the correlation of this effect with the behavior of other types of mines.

2.4.2 Measurements of the Dynamic Characteristics of Anti-Tank Mines

A great majority of the anti-tank mine studies are similar in their principles of operation. When a force is applied to the spider of the pressure plate, the gap between the under side of the plate and the firing piston of the fuze closes, and the force is transmitted to the firing piston. When the force is sufficient to shear the shear pin in the percussion-type fuze, or to break the glass ampoule in a chemical fuze, the mine detonates. A theoretical study of the mine's dynamic characteristics is not easily made since the elastic limit of the materials of which the mine is constructed is generally exceeded, and an unknown amount of friction is present; initially, therefore, the experimental approach was followed.

Measurements were carried out on the following types of fuzes or mines:

Type Mine or Fuze	Type Measurement
American M1B1 fuze	Static and dynamic
American M1A2 fuze	Static and dynamic
American M4 fuze	Static and dynamic
German TMi-42 mine	Static and dynamic
German TMi-43 mine	Static and dynamic
American T6-E1 mine	Static and dynamic
Japanese J-93 mine	Static and dynamic
Japanese J-13 fuze	Static
Japanese Type 3 fuze	Static
Japanese Yardstick fuze	Static
Dutch Mushroom fuze	Static
French Light fuze	Static
Japanese Type A-2(a) fuze	Static
Japanese Type A-3(a) fuze	Static
Experimental T6-UN mine	Static and dynamic
Experimental S TMi-43 mine	Static and dynamic
Experimental S UN mine	Static and dynamic
Canadian indicator mine	Static and dynamic
Universal indicator mine M1	Static and dynamic
Universal indicator mine M2	Static

Static Tests

Static tests were made with a hydraulic testing machine. The fuze or mine to be studied was set in the machine and the force required for a given displacement was recorded. A sample force-displacement characteristic for a German TMi-43 (Tellermine-43) is shown in Figure 10. A complete description of the test procedure and results is to be found elsewhere.[5, 6]

Dynamic Measurements

The dynamic characteristic of a mine was studied by subjecting the pressure plate of the mine to various shock impulses. The force during the impulse was measured by means of a quartz crystal stack, an amplifier, and a cathode-ray recorder. The displacement of the pressure plate was measured by means of the motion of a coil placed in a magnetic field, an amplifier, and a suitable recorder. A photograph of the force-time function was obtained with one recorder and simultaneously a photograph of the force-distance function with a second. The value of the impulse was then found directly by measuring the area under the force-time function, and the value of the energy absorbed by the mine was found by measuring the area under the force-distance function. Different impulse forms[5] were obtained by drop-weight tests in which various types and sizes of weights were used, and by blast tests carried out on a laboratory scale with standard engineer blasting caps.

From these data the following conclusions could be drawn: (1) for a given type of mine the minimum energy required to detonate the mine is substantially independent of the type of shock impulse acting on the pressure plate; (2) for a given mine there is a definite relationship between absorbed energy and the maximum displacement of the pressure plate—the minimum energy required to detonate the mine is a point on the energy-displacement curve such that if the energy is less than this amount the mine does not detonate, and if greater the mine detonates; (3) for the drop-weight tests in which the test weight made a "perfect hit"[h] on the impact plate, there is a linear relationship between the energy absorbed and the kinetic energy of the weight.

[h] A perfect hit occurs when the test weight flat strikes the impact plate and the weight bounces approximately straight up, indicating that the flat was parallel to the plate at the moment of impact.

2.4.3 Indicator Mine Developments

At the time the drop-weight studies were being made, the Engineer Board urgently needed a device which could be used to evaluate the effectiveness against German mines of demolition methods of minefield clearance. The drop-weight studies showed that, among the mines available for study up to this time, the German TMi-43 was one of the most difficult mines to detonate with shock impulses. In view of this the decision was made to use the TMi-43

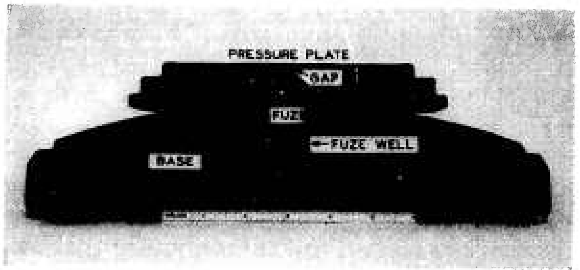


FIGURE 11. The TMi-43 indicator.

as a temporary indicator mine. On the basis of engineering data supplied to the Engineer Board, this German mine was substantially duplicated in the form known as the TMi-43 indicator. A method was devised so that this mine could be used as an indicator for shock impulses which were less than or equal to the minimum necessary to detonate the mine. In practice it was found that the range of this indicator was too small to give information on types of mines which differed appreciably from the TMi-43. Therefore the universal indicator mines M1 and M2 were designed.

The universal indicator mine M1 had an energy range approximately twice that necessary to shear the pin in the TMi-43 indicator. When studies of anti-tank mines were extended from German to Japanese types, it immediately became apparent that the Japanese mines were considerably harder to detonate by shock impulse. The characteristics of some Japanese mines were such that the range of the universal indicator M1 was insufficient to handle them. Accordingly the M2 universal indicator mine was developed; the M2 is simply a minor modification of the M1 in which the pressure plate on the M1 is replaced by a smaller and stronger one.

Apparatus Description

The TMi-43 indicator (see Figure 11) consists of three parts: the pressure plate, the base, and the fuze. The fuze is inserted in a fuze well in the base, and the pressure plate is screwed on tightly. The pressure plate (spot-welded type) acts as a spring with a constant for uniformly applied forces of about 3,000 psi and an elastic limit of about 250 lb. There is a gap between the under side of the pressure plate and the top of the firing pin (rounded knob in

FIGURE 12. Measuring the depression of the knob by the dial method.

Figure 11) of the fuze. The firing pin is held in place by the shear pin visible at the top of the fuze. When a force is applied to the pressure plate, the gap closes so that the force acts on the shear pin. A measurement of the

depression of the rounded knob can be related to the energy absorbed by the mine from the shock impulse. Thus the depression of the pin can be related to the probability of detonating other shear-pin mines which are operated by impulses less than that required to shear the pin in the TMi-43 indicator. A dial method of measuring the depression of the knob is shown in Figure 12.

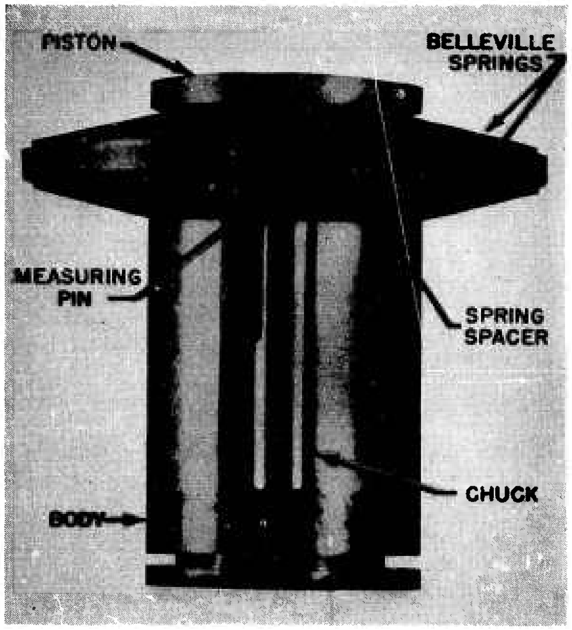


FIGURE 13. Phantom view of universal fuze.

The universal indicator mine M1 comprises an ingeniously designed universal indicator fuze and a modified TMi-43 indicator mine base and pressure plate. The modification consisted of enlarging the fuze well and pressure plate bushing. A phantom view of the universal fuze is shown in Figure 13 (about twice size). It consists of a piston which receives the force from the pressure plate, specially designed Belleville springs, a fuze body which sets in a fuze well in the mine base, a measuring pin, and a chuck which holds the measuring pin. Initially the measuring pin is set flush with the top of the piston. When a force is applied to the piston the springs deflect, the piston moves down, and the measuring pin moves down the same amount. When the force is removed, the springs return to the initial position, but the measuring pin is held by the chuck in the deflected position. A dial gauge with adapter is used to measure the deflection of the measuring pin, as shown in Figure 14. The load-deflection characteristic of the Belleville springs was chosen to simulate shear wire and to give an approximately linear energy-deflection curve in the complete mine. Hence a measurement of pin displacement, since this is linearly related to the energy absorbed by the mine, measures the dynamic characteristic of the mine that is substantially independent of the type of shock impulse. By resetting the pin the universal fuze may be re-used an indefinite number of times.

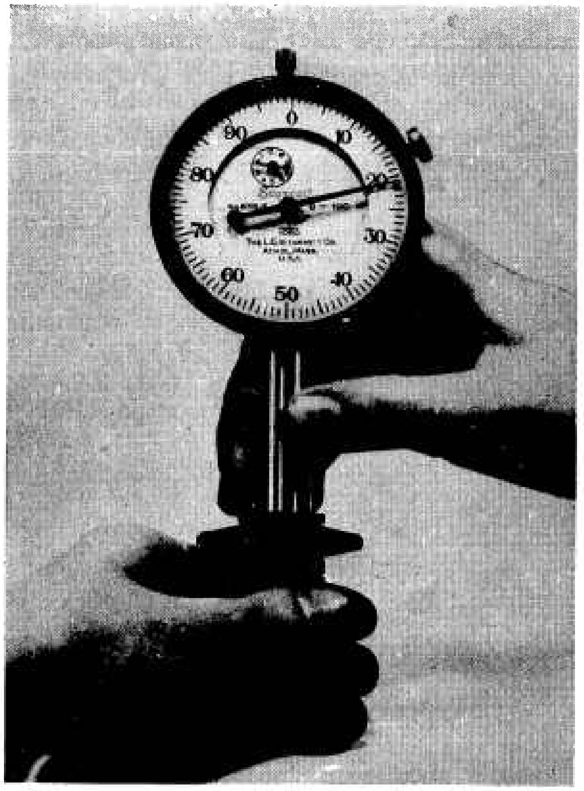


FIGURE 14. Measuring the deflection of the measuring pin with a dial gauge and adapter.

To increase the range of the universal mine by a factor of ten to twenty (in order to cover such mines as the Japanese J-13, J-16, Type 3, and Yardstick) the pressure plate was changed

for the M2 model. In the final design the diameter of the M2 pressure plate was reduced from 5⅞ in. (the diameter of the M1) to 2¼ in., and the thickness of the material was increased from 28 to 24 U. S. gauge. This procedure is obviously satisfactory, since the fuze is a force-measuring device and the mine as a whole is a pressure-measuring device.

CALIBRATION

The first calibration studies were carried out by means of drop-weight tests on unburied mines. In these calibrations a correction must be introduced for pressure plate area. As this correction was thought likely to be in error, and because it is particularly difficult to estimate effective pressure areas for some mine pressure plates, extensive calibration programs were carried out using explosive charges at Fort Belvoir, Virginia, and the Engineer Board Field Stations at Port Royal, Virginia, and Vero Beach, Florida. The field tests early showed that, without special precautions, the scatter in the data is so large that the calibration value can be determined only with a large amount of data. Since only a small number of enemy mines were available for the experiments, extensive precautions[6] were taken to make test conditions as uniform as possible.

To calibrate a given mine, fields sown with both the mine and universal indicator are subjected to blast from the same charge. The calibration value is the average reading D_p of universal indicator mines planted at a distance at which 50 per cent (or some other chosen fraction) of the subject mines are exploded. For this calibration to be meaningful the reading must be independent of the weight of charge, the type of soil, and the depth of burial of the mines; only then can the calibration be said to be consistent.

It has been shown theoretically[7] that it is quite easy to construct a mine of the shear-pin type that could not be calibrated in a consistent manner against universal indicator mines. This argument is based on the following reasoning. The energy absorbed by a buried mine usually depends in some unknown way upon both the peak pressure and the total impulse in the shock wave. For small charges and with the mine buried close to the charge, peak pressure is the dominating factor; for large charges and with the mine buried at some distance from the explosion, total impulse is the most important factor. Thus two constants of the mine p_∞ and I_∞ are involved which are defined by

$$kp_\infty = \int_0^{x_3} \frac{F(x)dx}{Ax_3}; \tag{1}$$

$$I_\infty = \left[2M\int_0^{x_3} \frac{F(x)dx}{A}\right]^{\frac{1}{2}}. \tag{2}$$

The symbols have the following meanings:

- A is the area of the moving member of the mine which is exposed to blast;
- M is the mass of the moving member, including the superposed earth cover;
- x_3 is the total displacement of the moving member required to actuate the mine (or to produce a given reading on universal indicator);
- $F(x)\,dx$ is the total static work required to displace the moving member through x_3 units.

If the two values of I_∞ and p_∞ computed for the average reading D_p of the universal indicator mine at which the other (or subject) mine shears are not the same, then the calibration will vary with charge weight. Fortunately, for most of the mines tested, these readings apparently were nearly enough the same so that a consistent calibration could be made.[6]

2.4.4 The Effect of Point Charges on Anti-Tank Mines

In conducting the program for the calibration of universal indicator mines a large number of tests using point charges were made. The data obtained from these tests have been analyzed and an empirical formula devised which allows the behavior of the universal mine to be predicted for a wide variety of conditions. In addition a method has been worked out whereby this formula can be applied to many foreign mines.[6]

This so-called *point charge formula* gives a convenient method for determining the proba-

bilities of detonating different mines for various soil conditions. It has been used to compute universal scale graphs for 0-in., 2-in., 4-in., and 6-in. depths of burial. The graph for 2-in. depth of burial is given in Figure 15. From these graphs the distance from the charge corresponding to an arbitrarily chosen probability of detonating any mine (which has been correlated with the universal indicator mine M1 or M2) can be determined for weights of charge

The versatility of the universal indicator mine is shown by the fact that it has been used to determine probabilities of detonation for enemy mines which are basically different in fundamental principle of operation, for example, the J-13 and J-16 Japanese anti-boat mines. Approximate probabilities of detonation[6] have since been determined also for the Japanese Type 3 (Flowerpot) mine, which is not of the shear-pin type.

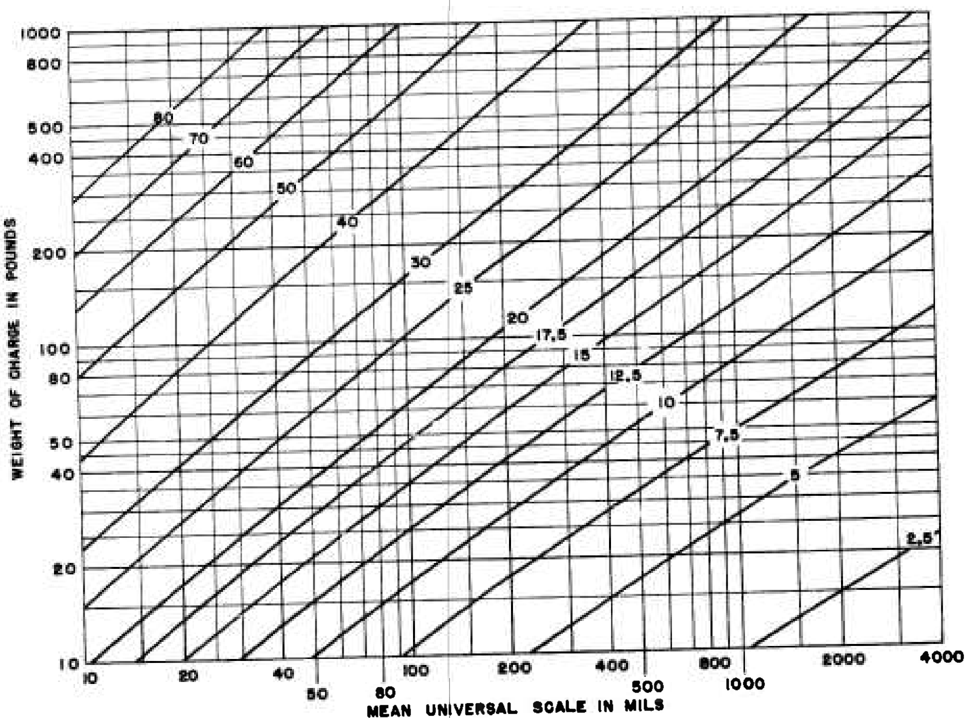


FIGURE 15. Curves showing distance (in feet) to charge for given weight and universal scale reading.

from 10 to 1,000 lb. While these graphs apply to cast TNT charges (cylindrical, with the length twice the diameter) hung at a scaled height above the ground (height in feet equal to cube root of the weight in pounds), they may be applied to other types of demolition weapons by using an equivalent weight of charge. Other theoretical studies of the effects of point and line charges on indicator mines have been carried out by Division 2, NDRC, in cooperation with Division 17.[7, 8, 9, 10]

2.4.5 Shock Tube

INTRODUCTION

In the preceding sections it was stated that dynamic characteristics of anti-tank mines have been studied by means of drop-weight tests and that these results have been used to calibrate, in terms of shock pressure impulses, enemy mines with the universal indicator mine. It was also noted that the majority of calibration data was accumulated in the field using

point charges. The drop-weight method of calibration is difficult or impossible to employ when the enemy mine does not have a well-defined flat surface for a pressure plate (e.g., the Japanese Yardstick mine). The field calibration

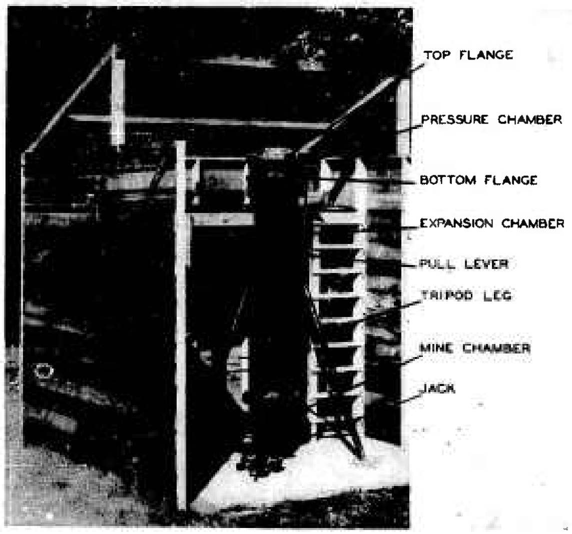


FIGURE 16. Assembly view of shock tube.

method is limited by variations in ground conditions so difficult to control that considerable data must be taken to establish a definite calibration value. It was therefore suggested that a large-scale model of a shock tube developed by Division 2, NDRC, for use in calibrating pressure gauges would be a useful tool in the calibration program as well as for other studies. In consultation with Division 2 a shock tube of 15.25-in. ID was designed on the basis of a theory[11] developed by Division 2. The necessary engineering work was completed, and a tube of the above dimensions was built and calibrated. (This tube was subsequently given to the Engineer Board for further experimental testing of mines.)

Description

The tube (see Figure 16) comprises a pressure chamber, an expansion chamber, and a mine chamber. Compressed gas from an air compressor or dry nitrogen tank is put into the pressure chamber through a connection (see Figure 17). The pressure chamber is formed by two aluminum diaphragms clamped between the flanges at the top of the tube. A round-pointed knife blade is placed in the region between the diaphragms and attached to an external arm in such a manner that the center of the bottom diaphragm may be cut by pulling this lever arm down. It has been found that, when the chamber pressure is greater than or equal to 70 per cent of the static pressure required to burst the diaphragm, the diaphragm will burst when cut by the blade.

The shock wave formed when the bottom diaphragm bursts travels down the expansion chamber and is reflected by the ground surface in the mine chamber. The reflected wave travels up the tube to the top diaphragm and is, of course, reflected again. This second reflection is only about 30 per cent of the amplitude of the first and consequently does not cause appreciable error in studying the effect of shock impulses on mines. A baffle has been built in the expansion chamber below the bottom diaphragm in order to catch, or at least slow up, fragments from the bursting diaphragm. The mine chamber at the bottom of the tube rests on a hydraulic jack so that it may be removed easily.

Calibration

A tourmaline crystal pressure gauge was obtained from Division 2, and suitable recording equipment was built to make pressure-time measurements of the shock wave. Figure 18 shows a calibration curve of the peak pressure in the shock impulse as a function of chamber pressure (obtained using the baffle). The calibration studies show that the peak pressures repeat in successive tests within a 5 per cent experimental error. The time duration of the shock impulse obtained for various chamber pressures was nearly constant and independent of the pressure. Other experiments indicate that the pressure at the center of the tube is about 5 per cent greater than the pressure at the side.

Mine Tests

During tests for the calibration program mentioned above, mines were placed in the chamber in order to determine the effect of

shock impulses. These tests brought out decisively that the compactness of the soil above and below the mine may be responsible for as much as a 30 or 40 per cent variation in calibration value, confirming results previously obtained from the field trials.

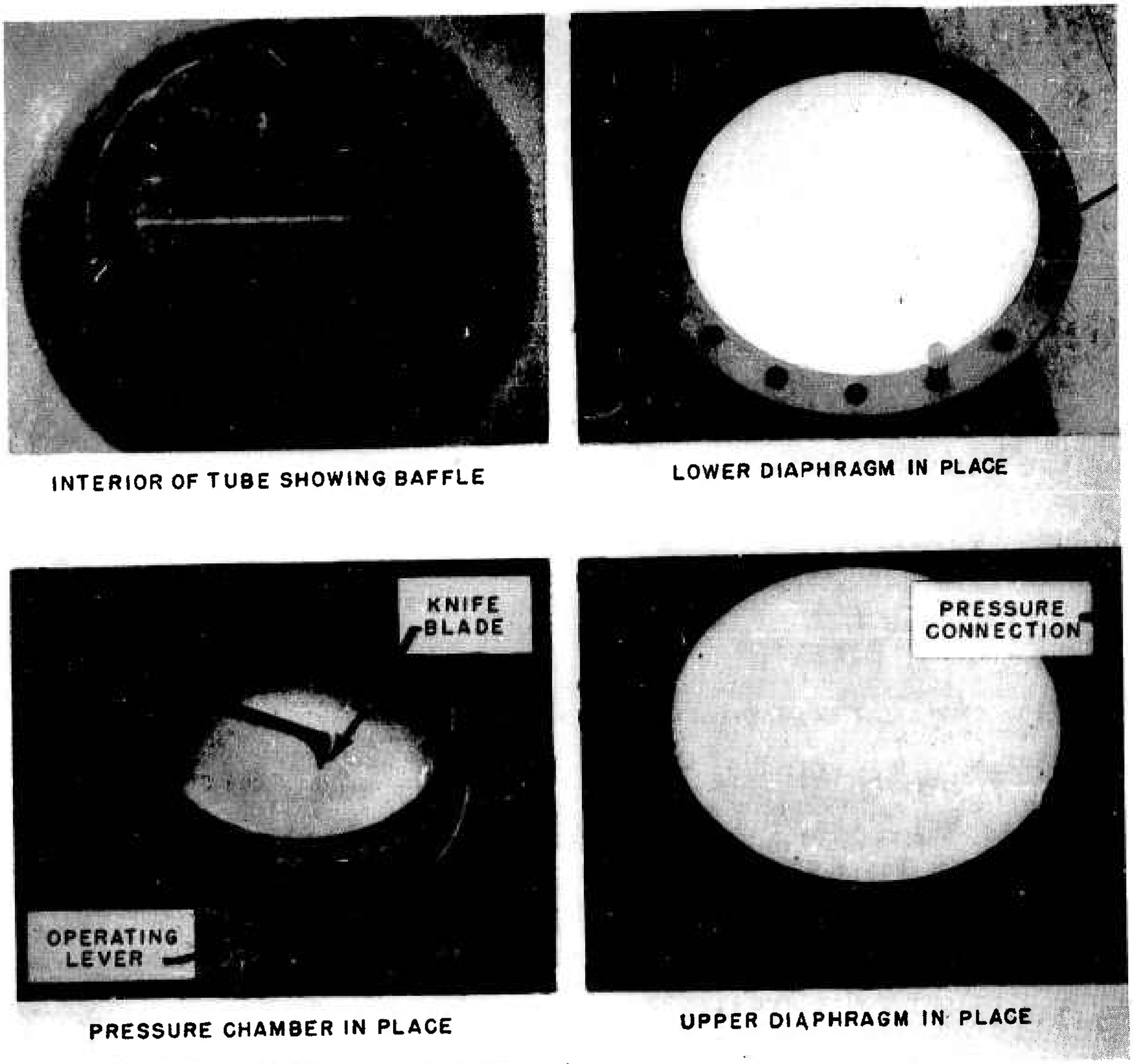


FIGURE 17. Views of shock tube.

Future Studies Using the Shock Tube

Sufficient tests have been made using the tube to show that the shock impulses repeat in successive tests. Thus comparative tests can be carried out with an indicator mine to measure the following: (1) effect of depth of burial in a soil of given type (controlled moisture content, etc.), (2) effect of different types of soil on a mine at a given depth, (3) effect of moisture content of soil, (4) effect of density of soil, (5) effect of temperature of soil, (6) effect of hardness of soil, and (7) correlation between indicator and enemy mines.

In addition to these studies, shock tubes can be used to analyze the effect of impulse on any device which is inserted into the chamber. Experiments of the type mentioned above have not been carried out, as the tube calibration was completed just prior to the cessation of hostilities.

The present shock tube is limited to peak pressures in the shock wave of less than about 150 psi. Tests have shown that this maximum is not sufficient to detonate the Japanese antiboat mine and the Type 3 (Flowerpot) mine. It may therefore be desirable to build a new tube which will go to higher peak pressures. It is believed this may be done using the same basic design by increasing the wall thickness of the tube, flange dimensions, and bolt diameters (i.e., by constructing a larger scale model).

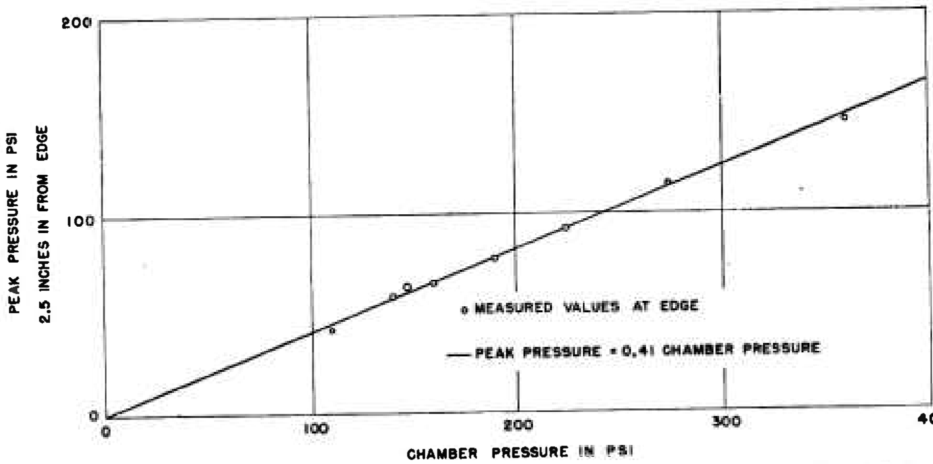


FIGURE 18. Peak pressure as a function of chamber pressure in shock tube. Baffle in place.

2.4.6 Auxiliary Design Studies

In addition to the investigations described heretofore, certain auxiliary design studies were carried out in connection with the development of demolition clearance devices by the Engineer Board and the reproduction of certain enemy mines. These studies are summarized briefly in this section.

FIRING DEVICE FOR PROJECTED LINE CHARGE[12]

The *projected line charge* [PLC] is a demolition device for clearing minefields which has been developed by the Engineer Board Field Station, Vero Beach, Florida. The device[14] consists of a flexible charge about 300 ft long and 3 in. in diameter (4 lb per ft explosive weight), a rocket and rocket launcher for projecting the charge across a minefield, an amphibious sled for storing and transporting the charge, and a firing device for first igniting the rocket and then detonating the charge. The charge is made of composition C-3 and is wrapped around a nylon rope that extends through the center of the charge. A nylon sock is then pulled over the charge and tied to the rope at intervals of about 6 in., giving a link sausage appearance to the assembly. Initially the charge is flaked into the sled under a plywood cover. When the rocket is ignited, a steel cable, which connects the rocket to one end of the charge, rips off the cover, allowing the charge to be dispensed as the rocket travels out. After the rocket has burned out and the charge has come to rest the charge is detonated. The firing device must be able to ignite the rocket and then detonate the charge by remote control (e.g., from inside a tank).

A firing device which has the following characteristics was designed for the Engineer Board: (1) electrical firing of the rocket and charge, using a standard engineer blasting machine; (2) complete waterproofing of all switches and cables; (3) pull-wire arming switches arranged in such a manner that the pull wire which arms the charge cannot be

removed until the wire which arms the rocket has been pulled; (4) a safety switch in the sled which arms the charge when the rocket leaves; (5) with the igniter and detonator wired up, the switch circuit shorts both circuits prior to actuating the arming levers.

The Amphibious Snake, M4[13]

The amphibious snake M4, a cooperative development of the Army Engineer Board, the U. S. Marine Corps, Ordnance Department, ASF, and NDRC, is a demolition device for use in amphibious landing operations. It consists of a 45-ft section of standard demolition snake M3, a rocket motor to drive the snake, a nose which causes the snake to plane on the surface of the water, and suitable arming, firing, and safety devices. In Figure 19 the amphibious snake is shown mounted on an LVT, in operation, and after coming to rest.

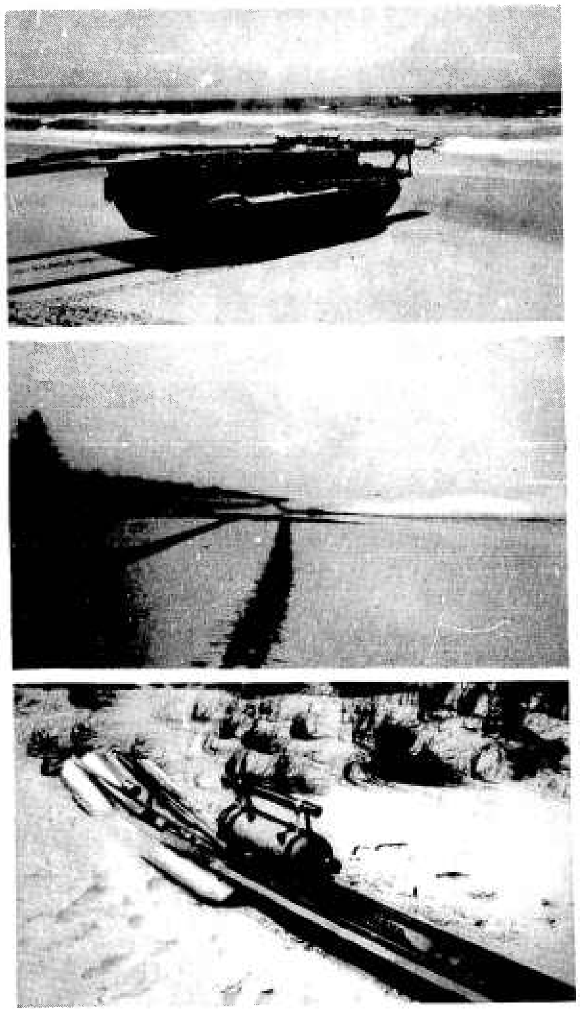


FIGURE 19. The amphibious snake (*top*) on the LVT, (*middle*) striking the beach, and (*bottom*) after coming to rest.

The portions of the development in which Section 17.1 was active were: (1) designing workable production models of the triple-rocket motor-mount assembly originated by the Rocket Division, Ordnance Research and Development Center, Aberdeen Proving Ground; (2) designing a suitable locking device to hold the snake prior to launching from the LVT; (3) designing a nose to control the snake so that a straighter course is followed; (4) designing motor brackets and an arming device for the single-rocket motor developed by Division 8, NDRC.

The snake nose shown in Figure 20 was designed by Division 12, NDRC, at the request of Section 17.1. The outstanding characteristic of this nose is its lateral stability, i.e., it tends to keep the snake traveling on a straight course. Field testing of this nose was done with the cooperation of Section 17.1.

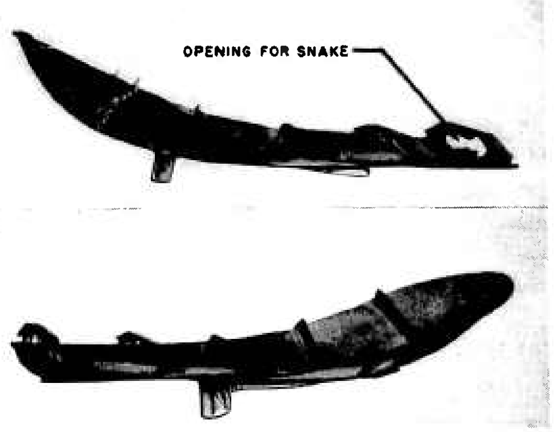


FIGURE 20. Views of boat nose.

Duplication of Enemy Mines

From time to time during investigations of characteristics of anti-tank mines, Section 17.1 was requested by the Engineer Board and/or Army Ordnance to draw up specifications for

small-scale production in this country of certain enemy mines. Among these were the Japanese J-13 and J-16 anti-boat mines, the Japanese Yardstick mine, the German TMi-43, and the Japanese Type 3 (Flowerpot).

In connection with the duplication of the anti-boat mines, a rather extensive program[6] was undertaken in cooperation with Division 2, NDRC, in comparing the reaction to underwater shock impulses of original Japanese mines and the U. S. replicas.

In many instances it would have been impossible for the Army to study the effect of its demolition clearing devices on enemy mines were it not for the availability of the replica mines, as very few enemy mines were brought back to this country. Thus the best substitute procedure for conducting experiments with enemy mines directly was to use copies which simulated as nearly as possible design characteristics of original samples.

2.4.7 Evaluation and Conclusion

The indicator mine development and the associated programs have proved in practice to be much more useful than was initially expected. This is due primarily to the very capable handling and direction of the work by the Gulf Research and Development Company, Pittsburgh, Pa., under contract with Division 17. One final result of the investigation, a formula which predicts for a wide range of explosive charges probabilities of detonating various enemy mines buried at different depths and in different soil conditions, is believed to be a major accomplishment. Without this and other contributions described in this chapter, it would have been difficult, if not impossible, to conduct the very extensive explosive mine-clearing program carried on by the Armed Services.

It is difficult to conclude a report such as this without considering the prospects of a future research program. It is readily apparent that the problems involved in demolition clearance of anti-tank mines are so complex that they cannot be handled adequately by other than trained technical personnel. Since the land-mine problem is a continuing one to which a solution has not yet been devised, the question may be appropriately raised as to what agency or agencies will continue the investigation. It is assumed that the various branches of the Army will continue their programs. It may be concluded, however, that this work will not progress as rapidly and satisfactorily by itself as it would if other technical organizations were able and willing to cooperate. For example, it is doubtful whether the Army will have the personnel and facilities to continue investigations made possible by the design and construction of the shock tube, and this instrument has as yet been exploited only to a limited extent. It is strongly recommended therefore, that the peacetime agency which ultimately succeeds NDRC include anti-tank mine clearance in the program it prosecutes.

Chapter 3

MAGNETIC CHARACTERISTICS OF VEHICLES AND MAGNETIC LAND MINES

3.1 INTRODUCTION AND SUMMARY

THIS CHAPTER describes investigations of the magnetic fields beneath and around tanks and other motorized vehicles and the development of firing devices for land mines which are actuated by the magnetic field of a vehicle passing over them. The purpose of the investigation was to ascertain how difficult the problem of degaussing tanks might be and how effectively magnetically operated mines might be employed against armored vehicles, including, as a corollary, investigation of the detection of mines containing quantities of ferromagnetic material.

In order to obtain the necessary measurements in connection with the study of the magnetic fields of vehicles a sensitive automatic recording magnetometer was developed. Six units were constructed so that complete measurements of the magnetic fields of vehicles could be obtained by driving the vehicles over the sensitive units. A study of the measurements showed that strong magnetic fields capable of discharging mines of suitable design are produced at the surface of the ground beneath all types of vehicles. The vertical component was found most appropriate for operating a mine because the maximum values of that component occur predominantly beneath the vehicle and with a more regular distribution than for either the longitudinal or transverse components. Degaussing of vehicles is not considered to be a practical countermeasure because the fields are so complicated as to require complex arrangements of degaussing coils for any fairly satisfactory neutralization of fields. Also, changes in the currents flowing in the coils would be required for each change of heading of the vehicle for the effect of degaussing to be relatively complete.

Two different magnetic firing devices for land mines were developed. The Department of Terrestial Magnetism of the Carnegie Institution of Washington developed a mechanical device, and the Gulf Research and Development Company an electronic device. Both are designed so as not to respond to slow changes in the earth's field, but to fire the mine when the vertical component of the magnetic field changes rapidly by more than a critical value. This value can be set as low as 50 milligauss. Several units of each device were made and after successful demonstrations were delivered to the Engineer Board for further study and evaluation.

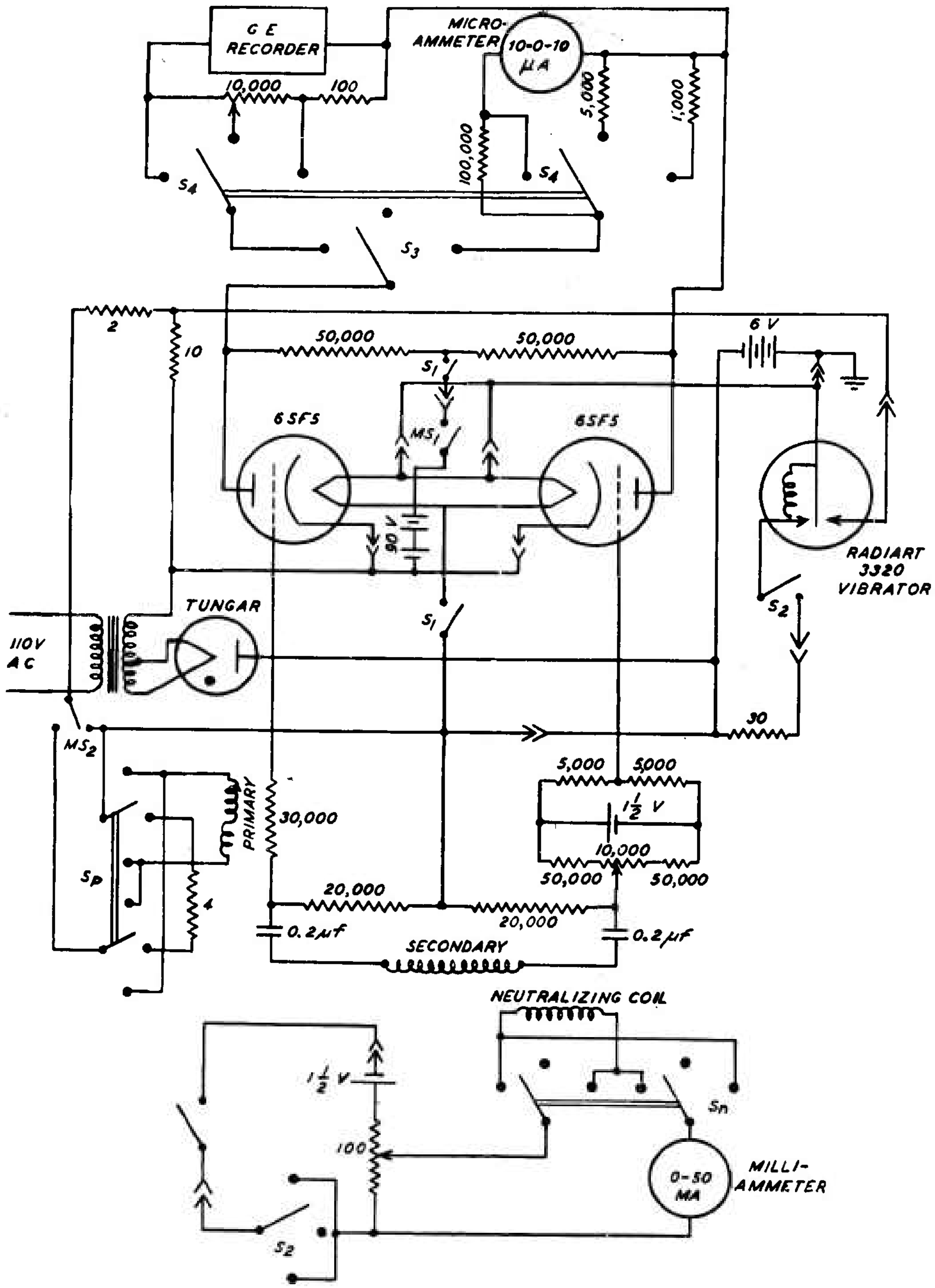
A detector was developed which can detect a ferromagnetic object the size of a land mine at a distance of about 4 ft. It has been described in Chapter 1 and will not be discussed here.

3.2 MAGNETIC FIELDS OF VEHICLES

In order to study the feasibility of using magnetically operated mines against vehicles and to work out possible countermeasures, detailed information on the magnetic fields of the vehicles is needed. The amount of data required and the limited availability of vehicles for study indicated the use of automatic recording instruments. After completion of the instruments, measurements were made at the Aberdeen Proving Grounds on the fields of eleven vehicles.[3]

3.2.1 Method of Measurement

The CIW Marine Magnetometer[1] was adopted as an automatic recording instrument. The sensitive unit of the magnetometer consists of a Permalloy wire 12 in. long and 0.027 in. in diameter. Around this is wound a single-layer coil of about 200 turns—100 turns wound in one direction and 100 turns in the other direction. A separate secondary coil of between 10,000 and 20,000 turns surrounds the primary coil. When the system is properly adjusted, the deflection of a galvanometer in the secondary circuit on making or breaking the primary circuit is proportional, over a range of several



NOTE: SYMBOL ->>- DENOTES CONNECTION OF EACH OF SIX UNITS TO COMMON CIRCUIT

FIGURE 1. Electronic circuit of six-element recording magnetometer.

hundred milligauss, to the field in the direction of the Permalloy wire.[a] A neutralizing coil completely surrounding the element can be used in several ways. It can be used to neutralize part of the field so as to bring the instrument into its range of linearity, or it can be used to neutralize the entire field, as shown by zero deflection of the galvanometer upon making or breaking the primary circuit, giving a null instrument, with the field being proportional to the neutralizing current. In the use of the instrument described here, the coil is used to neutralize the earth's field so that the instrument will read only the field due to the vehicle.

The instrument can be made continuous-reading by exciting the primary circuit with half-wave alternating current. This requires a commutating device in the secondary circuit in order that the output may be read on a d-c meter. This is done electronically by applying the primary exciting voltage to the grids of a pair of triodes connected in push-pull. The ends of the secondary coil are also connected to the grids of the triodes. The blocking impulse from the primary circuit is sufficient to make the tubes cut off during the half-cycle that the primary current flows. The difference between the plate currents of the tubes, which is proportional to the voltage in the secondary coil and thus to the magnetic field, is read on a microammeter or recorded on a General Electric photoelectric recorder. The calibration is usually 1 μa for 10 milligauss. The primary excitation is obtained either from a vibrator or, preferably, from a half-wave Tungar rectifier if 110-v alternating current is available. Figure 1 gives the circuit of one of the units, and Figure 2

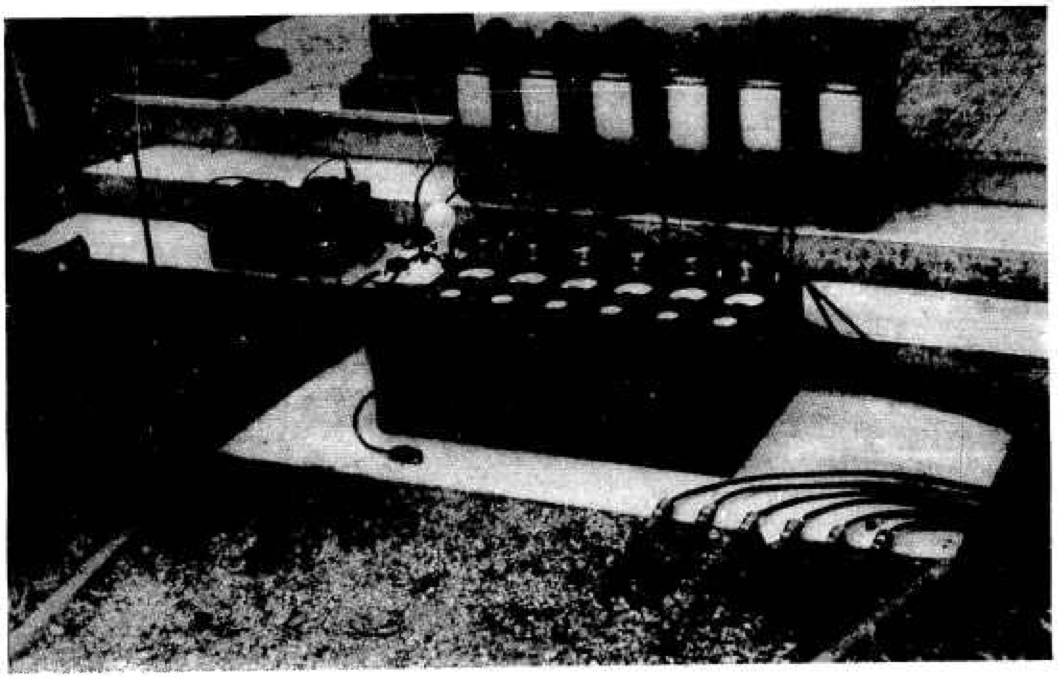


FIGURE 2. Complete six-element recording magnetometer.

[a] A rough explanation of this follows. The Permalloy may be considered as being composed of two parts inside the two halves of the primary. When the primary circuit is open, each half of the Permalloy has a flux, in the same direction for each half, which is proportional, over a limited range, to the field H. When the primary circuit is closed, the two halves are saturated in opposite directions to the saturation flux-density B. The changes in the fluxes in the two halves are proportional to $(+B - kH)$ and $(-B - kH)$. The deflection of the galvanometer is proportional to the flux change in the secondary, which in turn is proportional to the sum of the flux changes in the two halves of the Permalloy. Since this sum is $-2kH$, the deflection of the galvanometer is proportional to H.

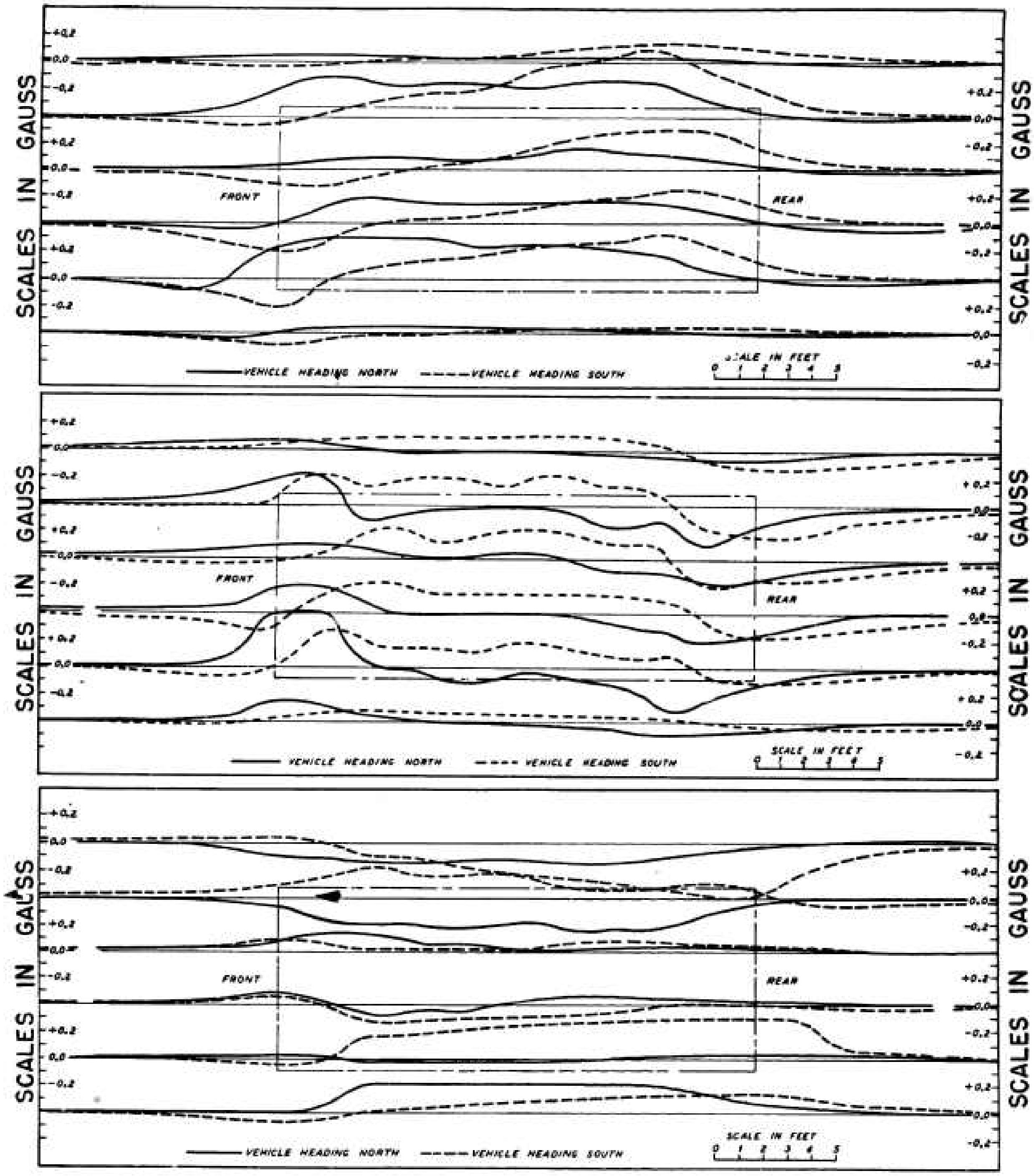
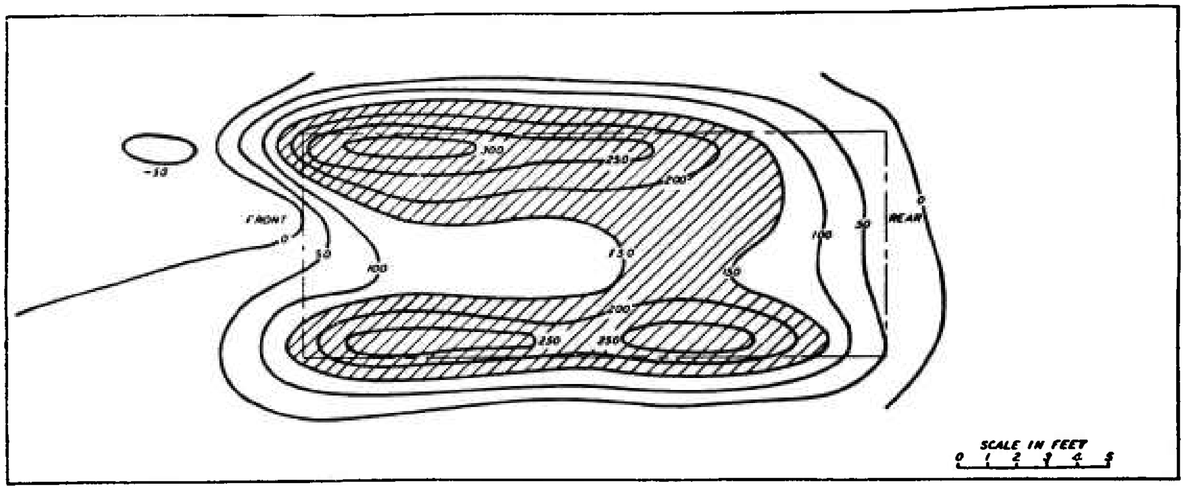


FIGURE 3. Magnetic fields beneath an M-4 medium tank for both northerly and southerly headings: (*top*) vertical field, (*middle*) longitudinal field, and (*bottom*) transverse field.

is a photograph of the complete six-element recording magnetometer.

The magnetometer elements were mounted in six weatherproof brass tubes about 1 in. in diameter and 6 in. long. Holes and troughs were dug so that the elements could be mounted to point east, south, or down at six points spaced 28 in. apart on an east-west line. The spacing was so chosen that, for tanks, elements 2 and 5 were under the tracks. The drivers were instructed to drive at uniform speeds, and marks were made on the records at the times of first and last contact of the vehicle with the elements. Each vehicle was driven on both north and south headings for all three components of the field.

A typical set of data is shown in Figure 3, in which are plotted the three components of the field of an M-4 medium tank for both north and south headings. The rectangle represents the plan outline of the tank. The six straight lines are the lines of measurement and are also the base lines of the graphs of the field components.



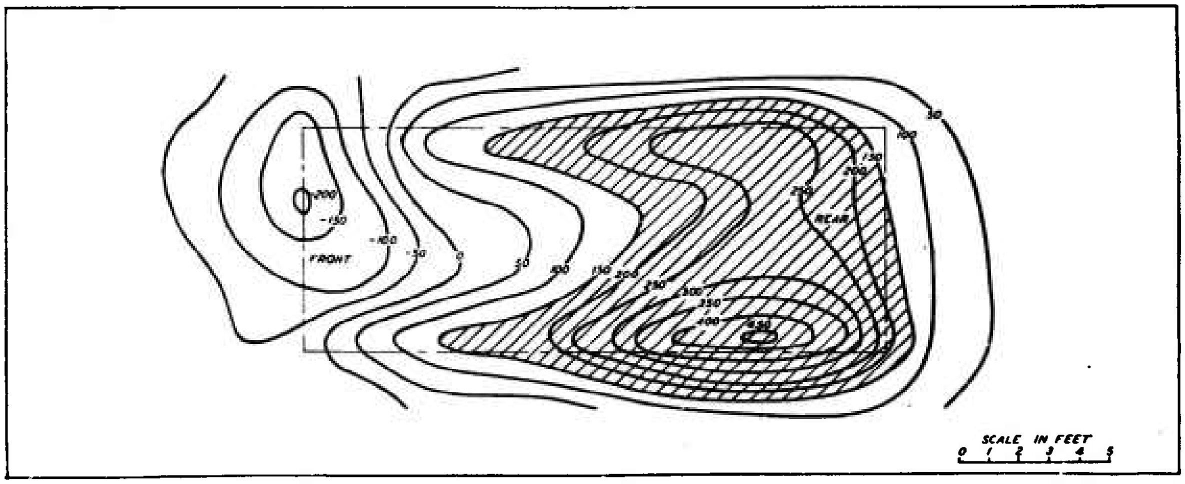


FIGURE 4. Contour maps of vertical magnetic field in milligauss beneath an M-4 medium tank when (*top*) heading north and (*bottom*) heading south.

3.2.2 Analysis of Magnetic Field of M-4 Medium Tank

An examination of Figure 3 reveals some interesting features. The fields are practically zero at a distance of 10 ft before or behind the tank, but the records do not extend far enough laterally to show this decrease. The

vertical field is much less irregular than the horizontal fields and has a considerable value over a larger area under the tank than do the others. These and other considerations make it desirable that magnetic anti-tank mines be designed to operate on the vertical magnetic field of the vehicle. For this reason, only the vertical component of the field will be analyzed in any detail.

$$Z_p = \tfrac{1}{2}(Z_n + Z_s),$$
$$Z_i = \tfrac{1}{2}(Z_n - Z_s).$$

Here Z_p and Z_i are the permanent and induced fields and Z_n and Z_s are the total fields for north and south headings, respectively. The "permanent" field is not permanent in the usual sense but is probably largely due to magnetism induced by the earth's vertical field and would

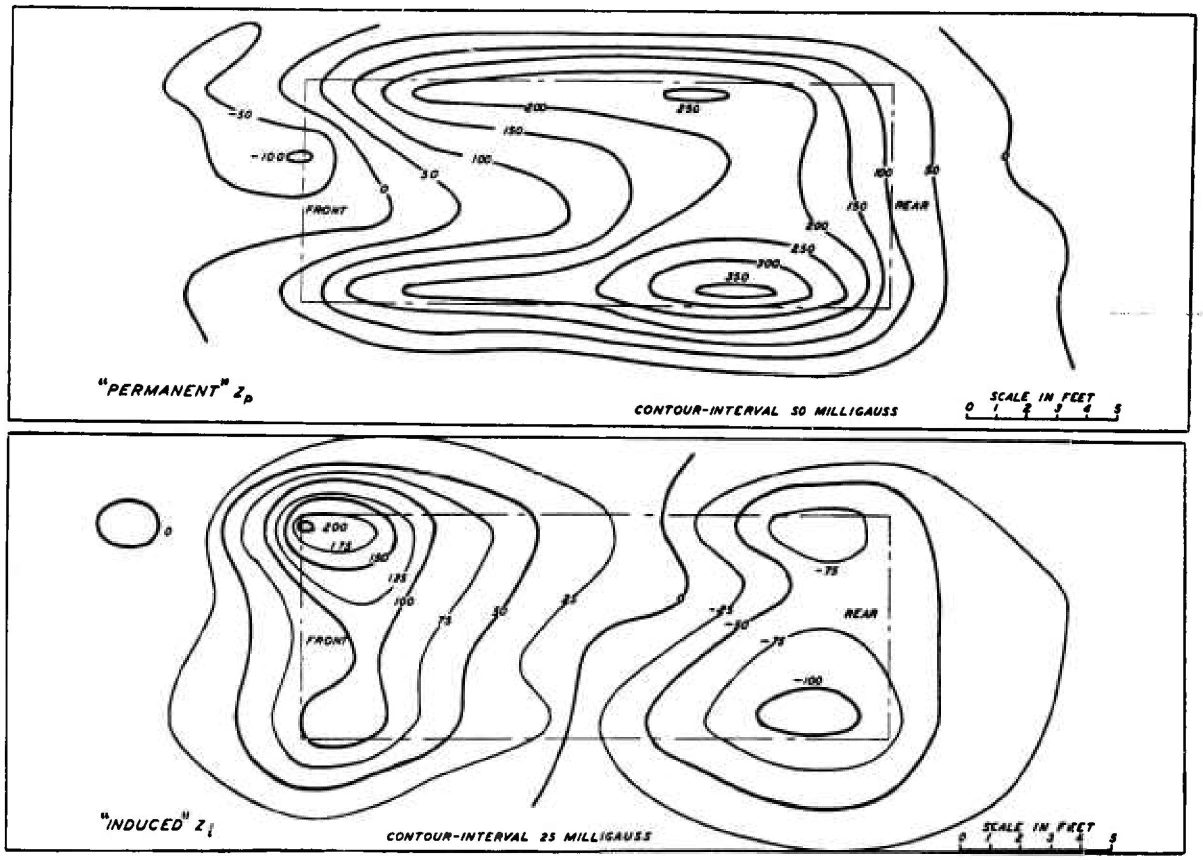


FIGURE 5. Contour maps of vertical fields of an M-4 medium tank: (*top*) "permanent" field and (*bottom*) "induced" field.

A better picture of the vertical field is given by the contour maps of Figure 4. The cross-hatched regions show where a firing device set for 150 milligauss will be actuated. There is considerable difference between the fields for the two headings of the vehicle. If we assume that the total field is the sum of a permanent field and an induced field which changes sign with the heading of the vehicle, we can write

change with magnetic latitude. The "induced" field is attributed to magnetism induced by the earth's horizontal field, and will be proportional to the cosine of the magnetic heading of the vehicle. Figure 5 shows contour maps of the permanent and induced fields.

Examination of Figure 5 shows that both Z_p and Z_i are roughly laterally symmetric, while Z_p is roughly longitudinally symmetric and Z_i

longitudinally antisymmetric. If we consider the fields as being made up of symmetric and antisymmetric parts, and neglect the smaller part, we will obtain fields which will differ from the actual fields by an amount which is never larger than 60 milligauss and which will be much more susceptible to a theoretical treatment. The results of this process are shown in Figure 6, which gives contour maps of the laterally symmetric, longitudinally antisymmetric part of the induced field, and the laterally and longitudinally symmetric parts of the permanent field.

If degaussing of the tank is to be done, it would be convenient to devise a distribution of currents or magnetic material above the plane of measurement whose magnetic field at the plane of measurement shall approximate the observed field of the tank. This can be done by expressing the observed field as a double Fourier series expansion and then expressing the field due to the model in the same sort of expansion. The adjustable parameters involved in the model can then be chosen to give the best fit between the observed coefficients and those of the model. The mathematical details of this procedure may be found elsewhere.[3a] Figure 7 shows contours of the current function obtained in this way which, at a height of 4 ft, will give at the plane of observation the laterally symmetric, longitudinally antisymmetric induced field shown in Figure 6.

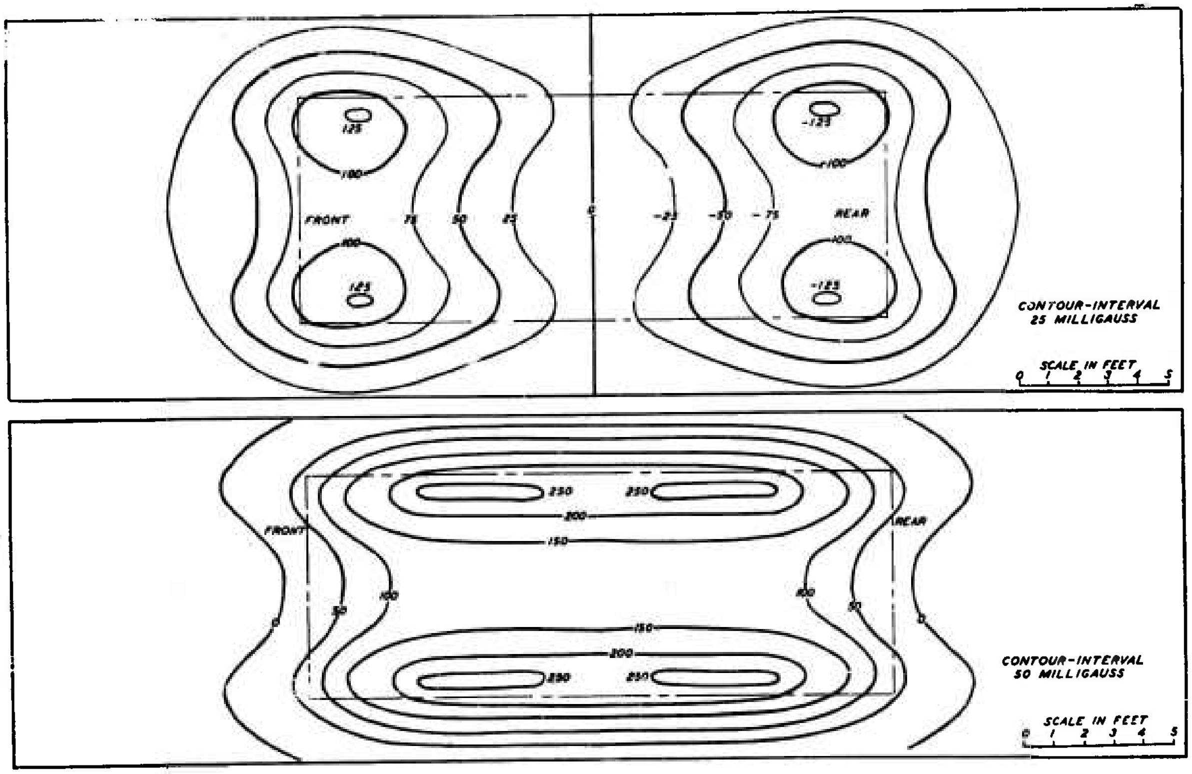


FIGURE 6. Contour maps showing (*top*) longitudinally antisymmetric, laterally symmetric "induced" vertical field of an M-4 medium tank and (*bottom*) longitudinally and laterally symmetric "permanent" vertical field of an M-4 medium tank.

3.2.3 Measurements on Other Vehicles

Measurements of the magnetic fields of ten other vehicles were made, but the data were not analyzed. If desired, the data could be treated in the manner outlined in the previous

section. The profiles of the fields may be found elsewhere.[3b] The results are summarized in Table 1. This table includes the maximum values of each of the three components of the field under the vehicle, the maximum sensitivity required of a detonator to insure firing no matter what part of the vehicle passes over the mine, and the estimated distance from the vehicle at which firing may take place for mines having a sensitivity of 50 milligauss.

TABLE 1. Maximum fields produced by vehicles, sensitivity required of mine to assure detonation, and maximum distance from vehicle at which firing could take place for mine with sensitivity of 50 milligauss.

Vehicle	Maximum field under vehicle			Sensitivity required of mine to assure detonation			Distance from vehicle at which mines of ±50 milligauss sensitivity could be fired		
	Vertical	Longitudinal	Transverse	Vertical	Longitudinal	Transverse	Vertical	Longitudinal	Transverse
	milligauss	milligauss	milligauss	milligauss	milligauss	milligauss	feet	feet	feet
M-4 Medium tank	450	400	290	150	180	50	5	4	3
3-in. Gun carriage	460	310	340	200	130	100	4	8	4
British cruiser-tank	320	320	280	100	100	60	2	5	2
Half-track	510	600	630	200	150	180	1	4	9
Scout-car	120	90	140	70	50	40	[illegible]	2	5
6-ton 6x6 Truck	170	120	130	70	70	50	2	4	4
Command car	150	120	70	60	40	40	1	2	1
¼-ton 4x4 Truck	130	120	100	80	50	70	0	2	1
¼-ton 4x4 Truck	100	80	90	60	60	70	1	2	1
37-mm Gun carriage	140	100	120	50	50	50	2	3	4
37-mm Gun carriage	100	110	100	60	80	60	1	2	1

For all the vehicles the vertical fields are more uniform than either the transverse or the longitudinal fields. The distance at which premature firing may take place could be greatly reduced by decreasing the sensitivity so that fields of 100 or 150 milligauss would be required for detonation. It should be remembered that the fields would vary with the magnetic latitude, with the data of Table 1 applying in the middle northern latitudes.

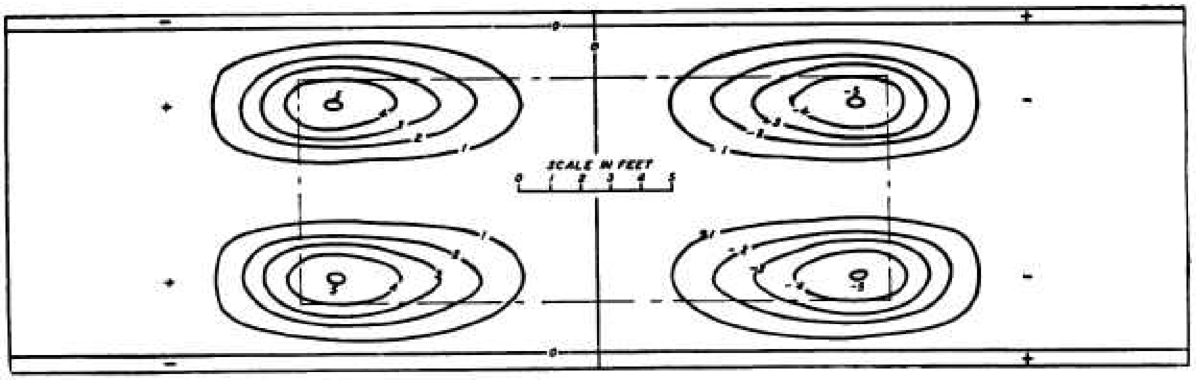


FIGURE 7. Contour maps showing the current function in arbitrary units at a height of 4 ft which fits best the observed values of the longitudinally antisymmetric, laterally symmetric "induced" vertical field.

The vehicles tested may be roughly divided into two classes: track-laying vehicles and wheeled vehicles. In general, the records of the former are characterized by large and erratic values for all three components, while the fields of the latter are smaller and more uniform.

3.2.4 Possibility of Degaussing

A large part of the field of the tank in the middle latitudes appears to be due to magnetism induced by the earth's vertical field. This could be partially neutralized by an arrangement of

coils which would produce a distribution of north poles along the bottom of the side armor of the tank. That part of the field due to the earth's horizontal field could be neutralized by a system of coils which would approximate the current distribution shown in Figure 7. Unless arrangements, preferably automatic, are made to make this current in these coils proportional to the cosine of the magnetic heading of the vehicle, the compensation could be off for some headings by as much as 160 milligauss. It might perhaps be necessary to provide another adjustable current arrangement to neutralize magnetism induced in the tank by the earth's horizontal field on easterly and westerly headings. The magnitude of this effect was not measured but it should be smaller than that obtained on northerly and southerly headings.

It is probable that the presence of magnetically permeable material in the tank would enable a simple current distribution to produce a better fit to the field than would be expected from the simple treatment. This would simplify the problem. A rough estimate has been made[3c] of the amount of copper and current needed to do the degaussing. For a current of 5 amp from the 24-v electric system of the tank, about 1 kg of copper, suitably arranged in coils, would be required. Most of the records show major irregularities, and the records under the tracks show irregularities extending a few feet at most. The latter "fine structure" could probably be removed by local demagnetization or "deperming." It is probably out of the question for any practical degaussing system to compensate for the vehicle's magnetic field to such an extent that it would be incapable of actuating the most sensitive firing device possible.

3.2.5 Conclusions

The measurements on the magnetic fields of vehicles indicate that the use of magnetically operated land mines against vehicles is entirely feasible. The vertical component of the field is superior to the longitudinal and transverse components for firing a mine. To assure firing on the horizontal components of the field, a mine must respond to both positive and negative fields, which would often result in firing when the vehicle was not directly over the mine. On the other hand, if the mine responds only to positive vertical fields, an appropriate choice of sensitivity would insure its firing only under the vehicle. Magnetically operated mines need not be touched by the tracks or wheels of vehicles to be fired, permitting an area to be adequately mined with fewer units. They could be so adjusted that they would be fired only by the heavier armored units, permitting the lighter reconnaissance vehicles to pass over them unharmed.

Thorough degaussing and deperming of vehicles is out of the question if done simply enough to be practicable, although it could be done for mines of low sensitivity. One possibility that merits serious consideration is that of using magnetically operated mines of low sensitivity together with simple degaussing of our own heavily armored vehicles. This would permit our own vehicles, both lightly and heavily armored, to pass unharmed over minefields forbidden to armored vehicles of the enemy.

3.3 MAGNETIC LAND MINES

Since the measurements of the magnetic fields of vehicles described above had shown magnetically operated mines to be feasible, work was undertaken on the development of a magnetic firing device for land mines. Two entirely different devices were developed.

3.3.1 Mechanical Magnetic Firing Device

This magnetic firing device for land mines was developed at the Department of Terrestrial Magnetism, Carnegie Institution of Washington.[2] It depends for its operation on the mechanical motion of a sensitive magnet which takes place when the vertical component of the field changes. The construction is such that only rough leveling is required at the time of installation, while gradual changes in level and normal changes in the magnetic field are automatically compensated for.

The firing device consists of a magnet system suspended so that it is free to rotate about a horizontal axis when acted on by changes in the vertical component of the earth's field, and a

vane which rotates with the magnet system for gradual changes in the field but which lags behind for rapid changes, causing an electric contact to be made.

The magnet system consists of six Alnico magnets, 3/32 by 13/32 by 5/8 inches, mounted three each on two small tubular shafts as shown in Figure 8. A larger tube, which has an open portion to permit the insertion of the vane, serves as a hub connecting the two shafts. The vane is mounted on a very small steel shaft, the ends of which are seated in insulated pivot bearings in the ends of the larger tube so that around the magnet system. This is enclosed in a large tube about 2 in. in diameter and 6 in. long, as shown in Figure 9. This tube is nearly, but not quite, filled with oil and then sealed. The oil serves to damp the motion of the vane, making it unable to follow rapid motions of the magnet system.

If the earth's vertical field is suddenly increased, the south poles of the magnets move rapidly upward. The vane, however, lags behind and makes contact with the uninsulated arm, completing the electrical circuit about 0.1 second after the change of the field. The models

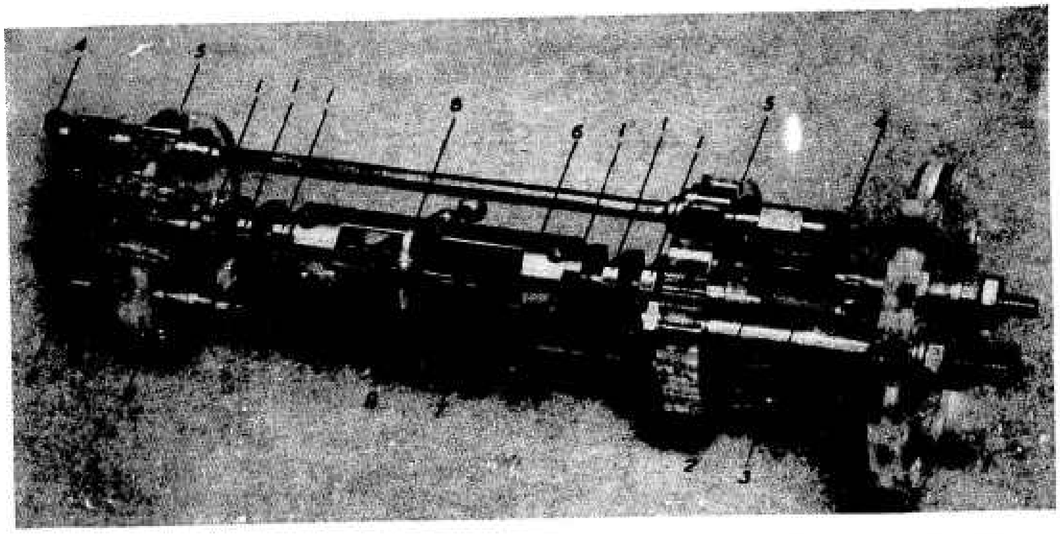


FIGURE 8. Magnet system and supporting frame of firing device (magnets, 1; tubular shafts, 2; suspension wires, 3; tension springs, 4; plastic plates, 5; tubular hub, 6; vane, 7; insulated arm, 8; contact arm, 9).

the vane is free to rotate about the axis of the magnet system. The entire magnet system is suspended by phosphor bronze wires which extend from flat springs through the tubular shafts to about the position of the middle magnet of each group of three. Only one of the suspension wires is electrically connected to the magnet system, the other being electrically connected to the vane. Two rigid arms, one with an insulated tip, are attached to the tubular hub. The vane is slightly unbalanced so that normally it rests against the insulated tip.

A frame of brass and plastic holds the flat springs to which the suspension wires are attached and forms a squirrel-cage structure constructed were sensitive to changes of 25 milligauss taking place in times less than 1 second. In other words, it will be actuated when a jeep is driven over it at a speed greater than 2 or 3 mph. For use against armored vehicles, the device could be made less sensitive by increasing the separation of the contacts.

Several possible variations in the use of the device present themselves. (1) The explosive charge need not be located in the same place as the firing device itself; e.g., it could be used to detonate a series of charges along a highway when a vehicle reaches one part of the highway. (2) The device could have remote control for arming and disarming, such as is used in harbor

mines. (3) It is believed that the device can be made so rugged that it may be dropped from aircraft into areas behind the enemy's lines. A great increase in ruggedness can be obtained by using a heavy oil and freezing it before the device is dropped.

A wide range of variations in sensitivity and time of response can be obtained, particularly for applying the device to marine use. The greater space and weight practicable for marine mines would permit much greater sensitivity and slower response, which would adapt the mine for use even against degaussed ships.

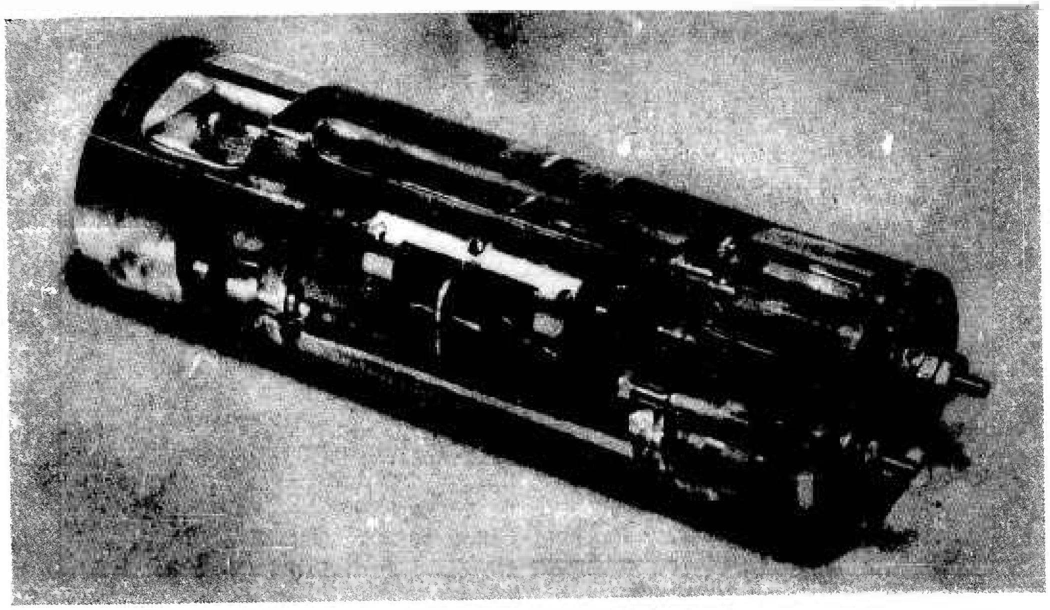


FIGURE 9. Firing device in tubular housing.

3.3.2 Electronic Magnetic Firing Device

This magnetic firing device was developed at the Gulf Research and Development Company[a] and is an adaptation of the device developed there for use in submarine influence mines (discussed in Chapter 4). The firing device is complete and self-contained; it may be used as a separate unit or attached to a standard antitank mine case as shown in Figure 10. The transparent plastic cover illustrated was selected for demonstration purposes only. The unit is sensitive to an increase of about 50 milligauss in the earth's vertical field and will be actuated by vehicles traveling from 1 or 2 to approximately 45 mph.

The basic principle of operation is essentially the same as that of the automatic recording magnetometer described in Section 3.2.1. The difference is that the output voltage of the secondary coil is used to trip a control tube which discharges a condenser through the firing cap, instead of being amplified and recorded on a meter.

The detector consists of two tiny matched cores of a high-permeability steel alloy, the primary coils for which are connected in opposition. The coils are excited to saturation by a relaxation oscillator, and the output voltage of the common secondary coil is proportional to the component of the magnetic field parallel to the cores.[b] The output pulses from the secondary are rectified by a small vacuum tube operating as a grid-leak detector. The rectified voltage is applied to the grid of the second tube, which amplifies the changes if they occur at rates corresponding to a prescribed range of vehicular speeds. In this way the effects of slow drifts are eliminated. The amplified voltage is applied to the grid of a small thyratron tube,

[b] Footnote a explains this relation.

causing it to fire when the voltage changes by an amount corresponding to a change in magnetic field of 50 milligauss or more. The thyratron tube discharges a condenser through the firing cap so that it is not necessary to have a battery of sufficient current capacity to fire the cap directly. Figure 11 gives a circuit diagram of the complete device.

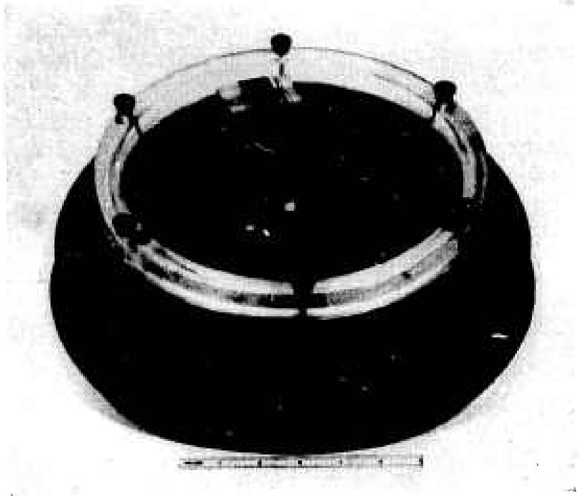


FIGURE 10. Electronic firing device mounted on standard anti-tank mine.

A compensating magnet is used to adjust the stationary magnetic field through the coils so that the device will operate at a point near the center of the linear portion of the detector-tube characteristic curve. This makes it possible to adjust the device for satisfactory operation in any magnetic field normally encountered throughout the world. It can be done for a given zone of operations before planting, provided the mines are not to be planted near large steel objects. Even so, the adjustment is easy to make in the field with the help of a simple test instrument.

When the mine is planted, the firing circuit is disconnected. The clockwork timing relay is set to connect the circuit after a selected interval which is adjustable from 5 minutes to 1 hour. An additional time delay is then provided by the charging time of the condenser.

The units constructed apparently have good characteristics of sensitivity, response to various vehicle speeds, and low battery consumption. Considerable care was taken to select circuits which would give uniform results without critical matching of tubes and other components, and to give as nearly uniform results as possible over the life of the batteries, but no attempt was made to design the unit for quantity production.

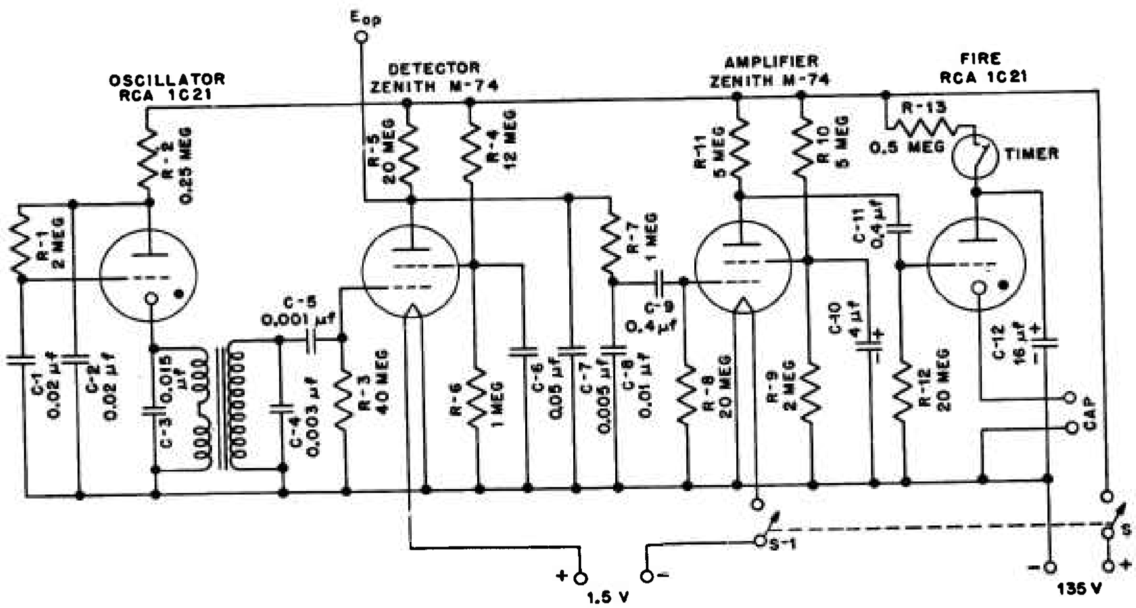


FIGURE 11. Circuit diagram for electronic firing device.

Chapter 4

CONTROL SYSTEM AND DETECTORS FOR SUBMARINE INFLUENCE MINES

By *F. L. Yost*[a]

4.1 INTRODUCTION[b]

SUBSURFACE MINES (referred to in this chapter as "submarine mines" or merely "mines") controlled from shore are widely used for harbor defense. A large number of mines are arranged in a pattern so that any vessel entering the harbor must come within the destructive area of one or more mines. Adequate signaling to shore from the mines and control of the mines from shore are necessary in order to protect friendly vessels.

At the time when the present work was undertaken it was usual practice to arrange mines in groups of nineteen, each connected to a distribution point by means of a current-carrying single-conductor cable. A single-conductor cable connected the distribution point to the shore installation. The mines installed by the Submarine Mine Depot, Fort Monroe, Virginia, were usually of the buoyant type, each so anchored by a cable (to a weight on the bottom of the ocean) that the mine was held a little below the surface of the water. The tilting of a mine by a vessel armed it by closing contacts that made it possible for the mine to be exploded either automatically or by manual operation at the shore station.

The initial buoyant mine had the advantage of not requiring any power to be supplied to the mine to operate the detector. The original control system operated on a current margin basis and required maintenance of voltages and currents within rather close limits. The system operated on a step-by-step basis; that is, when one mine was contacted, the control system had to step through all the mines, in order, until it reached the proper one. Only after that indication had been noted and the control had been released could the apparatus step on to another struck mine or around to its home position. Only one mine could be exploded at a time. It was felt that a frequency-control system might be developed which would eliminate the close margins and would at the same time afford a more flexible control. As a result, a project was set up with the Union Switch and Signal Company[1-4] for studies and experimental investigations of circuits used to operate mines at the Submarine Mine Depot, for the purpose of recommending possible improvements.

Complete circuit diagrams and descriptions of operations were drawn up for five different systems, all applicable to the then standard contact mines. The fifth system was very versatile and could be operated automatically, semiautomatically, or manually. Therefore, the first four systems were eliminated from consideration, and it was decided to build a model of the fifth system for the control of two groups of nineteen mines each. When this work was substantially completed, the possibility of influence-type mines replacing the contact-type was proposed.

The Coast Artillery Corps had decided that the influence-type mine was more satisfactory than the contact-type. For example, greater sensitivity and a higher percentage of actuation could be expected. The possibility of using influence-type mines rather than contact-type introduced new problems for the control system (e.g., supply of power for the detector). It was felt that any system developed should provide for the control of influence mines. Since the system under construction was not well suited for this purpose, work on it was dropped immediately. Plans were drawn up for a new frequency-control system which could be used with influence mines. This work was coordinated with work on a project by the Gulf Research and Development Company[5-15] on a magnetic detector and associated circuits for mines,

[a] Technical Aide, Division 17, NDRC.

[b] The control numbers for this project were CAC-1, OD-69, and OD-72.

and with work on a project by the Massachusetts Institute of Technology[16-23] on a sonic detector and associated circuits for mines.

This report deals with the frequency-control system for influence mines and the magnetic and sonic detectors.

4.2 MILITARY REQUIREMENTS

The features required for a successful control system are the following.

1. The apparatus must perform reliably.
2. The system must clearly and quickly indicate to the operator when a ship is within striking distance. If a ship comes within striking distance of several mines simultaneously, it is highly desirable that they should indicate simultaneously.
3. The warning should be both audible and visual. The audible signal may be a single-stroke gong to attract the operator's attention, but the visual signal must remain on until answered by the operator.
4. Any mine or group of mines must be capable of being exploded from shore, whether or not the presence of a ship has been indicated.
5. Detonation must never take place from any cause other than a deliberate act on shore.
6. Some means of testing must be provided so that the condition of all parts of the apparatus (except the detonation mechanism) can be checked from time to time.
7. If the mine mechanism requires power for its operation, the power must be supplied over the shore cable.
8. There should be no equipment other than fuzes at the distribution point (i.e., at the point at which the individual cables from the mines in a group are connected to the single shore cable which services the group).

The characteristics required for the magnetic detector are: (1) it should have a detection radius of 75 ft; (2) it must operate with, and as a complementary part of, the control system. In addition, it would be desirable if it were self-powered.

The specifications of the sonic detector are: (1) it should have a cone of influence such that the surface area to which actuations of the device are limited is a circle 140 ft in diameter, 70 ft above the mine; (2) as a countermining measure, the device should function only in the area described and at sound pressures less than 500 bars.

4.3 SUMMARY OF DEVELOPMENT

4.3.1 Control System

All the control requirements are met by a frequency-control system in which each mine signals to shore by means of a distinctive frequency when a boat is near. The control of the mine, both for testing and for firing, is provided by other frequencies (distinctive for each mine), and the power is supplied over the shore cables. The control system, as finally developed, will operate with any type of mine, the only requirements being that the mine contain an oscillator and that the output of the oscillator be changed by a substantial percentage when a detection is made, irrespective of the mode of detection.

4.3.2 Magnetic Detector

One of the detectors developed for use with this control system was an electronic magnetometer. This detector is not self-powered, but suitable provision is made for supplying power from shore through the control system. Many tests of the actual effectiveness of this detector have been made by plotting the courses of various classes of vessels (all degaussed) over a single line of five mines spaced 150 ft apart and at an average depth of about 75 ft. In these tests the mine-control apparatus gave actual firing indications for an average of 90 per cent of the passages over this single-line minefield. The percentage of indications varied from about 40 per cent for small vessels from 75 to 150 ft long to 99 per cent for large vessels (larger than destroyers).[14] The actual effectiveness of a complete minefield, such as might be used for harbor protection, would be much higher than these figures, as a more complete net of mines than the single line of five would

have to be traversed. Also, the effectiveness would be increased by the operator's judgment of the position of the ship relative to mines which give merely warning signals but not a second (i.e., firing) signal.

In the above tests the mines were on sea bottom, as would be the case in actual practice. When a detecting device is employed, a larger charge is used than would be needed for a contact-type mine and the mine is placed on sea bottom as a precaution against countermeasures.

4.3.3 Sonic Detector

Sonic detectors were developed for use with the control system. Complete circuits for an echo-type detector were reported; and two units were delivered to the Mine Depot and placed under continual test. This device worked and was being improved. Such improvements hardly seemed worth while, however, because of the necessary complexity of the device when used for controlled mines, and the fact that the device tended to fire on wakes of ships. Hence, further work on this type of device was discontinued. Since it seemed urgent that some sort of acoustic device be designed, preferably a simple one, work was then begun on a 15-kc listening-type detector to operate with the shore-control equipment. The device was installed at Fort Monroe, where its operation proved very satisfactory. Reports on the first two months of tests showed that not one boat passed within the destructive range of the mine (approximately 150 ft) without giving a firing indication.[23a] There were a number of times when the boats set the light off too soon. However, a small amount of premature firing was considered tolerable in order to keep the device extremely simple. The percentage of actuations within the destructive range of the mine was very high. For example, during one eleven-day period thirty-five courses were plotted of boats of all types (battleships to small patrol boats) which passed over the unit. There were no misses: 77 per cent of the actuations were within 150 ft and 23 per cent were over 150 ft away.

4.3.4 Complete System

In the final development, the unit of offshore equipment consists of thirteen mines, each connected by an individual cable and fuze to a common distribution box connected by a single cable to shore controls which may be as far away as eight miles. All energy transmission for functioning of the unit—which includes signaling from any mine to shore and testing or firing of any mine from shore—takes place over the single cable. Complete, independent control to and from each of thirteen mines over the single cable is maintained by energy transmission at a series of different frequencies and discrimination by means of suitable filters.

Each mine can detect the presence of a vessel as a result of a magnetic or sonic disturbance. It can send to shore a signal frequency specific to itself, indicating the presence of a vessel in its vicinity. It can accept from shore the signal frequency necessary for testing the condition of its detector and the signal frequencies necessary for its detonation.

The shore apparatus has provision for performing the following functions for a number of offshore units.[4] It supplies power to the mine apparatus. For each shore cable and group of thirteen attached mines it provides selective and indicating circuits which clearly indicate any change in the sonic or magnetic condition at each mine and at all mines. It supplies thirteen test frequencies and has a switching arrangement so that any one or group of these frequencies can be applied to any shore cable or group of shore cables. It provides the firing frequency and a switching arrangement so that this frequency can be applied to any shore cable or group of shore cables. The control system is flexible enough so that various types of detectors can be used with it; the indication receivers are the only part of the apparatus requiring modification with change of detector.

The entire mine development may be summarized by enumerating the advantages of the system, most of which were new at the date of its development. The system operates on influence mines on sea bottom, thus leaving the channel free of obstructions. It is stable, dependable, long lived, and gives reliable indica-

tions of ships. It has a simple, visible signal and an auxiliary audible signal, the two permitting judgment of proper firing time. It shows indications of all mines at all times on a very simple indication panel. Any one or any group of mines can be fired at any time, but only by deliberate action of the shore operator. The operation of the system can be checked and its sensitivity adjusted from shore. The system operates on a single conductor to each distribution point, has unit construction permitting expansion to cover needs of different installations, and uses individual plug-in type electric units to facilitate replacement and repair in case of trouble.

Original requirement No. 8 is not satisfied because it is necessary to place at the distribution point a 440- to 220-v transformer and some filter elements.

Early in 1943 officers of the Coast Artillery Board witnessed demonstrations of the control equipment, and it was decided that the development showed sufficient promise to warrant the building of two production samples for field tests. The development work terminated in June 1943 with the awarding of a contract by the Ordnance Department for the building of two five-group equipments comprising the control equipment necessary to operate five groups of mines and the detecting equipment for these mines. In each five-group installation, three groups were to be of the magnetic type, one group of the sonic type (i.e., the listening device), and one group a sonic detector of a type developed by the Naval Ordnance Laboratory (with suitable modification by the Submarine Mine Depot).

4.4 DESCRIPTION AND TECHNICAL INFORMATION

4.4.1 Control System with Magnetic Detector

A functional diagram of shore and mine apparatus used with the magnetic detector is given in Figure 1. The frequencies used and the assignment of different frequency ranges to specific purposes are indicated in Figure 2. The general arrangement of the mine, of the magnetic detector, and of the associated electric equipment is shown in Figure 3. The magnetic detector itself is placed in a long nonmagnetic housing extending above the main body of the mine. The complete assembly of the mine apparatus, as shown in Figure 4, contains seven vacuum tubes and has approximately the same number and kind of parts as a seven-tube radio receiver. To ensure long life and stability, the circuits are all carefully designed so that the loads of the vacuum tubes are much less than usual. The minimum tube life should be of the order of two years.

The magnetic detector is entirely electric in operation and has no moving parts. The detector coil, shown in Figure 5, is essentially a transformer, the secondary of which surrounds two primaries which are parallel to each other and which are each wound around a thin strip of high permeability material (Mu-metal). An exciter oscillator in each mine excites the primaries *oppositely* and with sufficient current to saturate the cores. The wiring and arrangement are such that, in the absence of any component whatsoever of magnetic field along the primary cores, simultaneous and opposite energizing of the primaries results in zero secondary voltage. If a component of magnetic field is imposed along the cores, it adds to the exciting field of one core and subtracts from the opposing one of the other core at every instant of an energizing cycle. The secondary voltages induced by the primary coils are therefore not equal and opposite, and they cancel each other only partially. The net result is a complex secondary voltage which for a detector placed in the earth's field has a minimum value for zero ambient field and increases with applied ambient field component.

A detector tube rectifies and amplifies the secondary voltage, delivering continuously a d-c voltage. As shown in Figure 6, the effective range through which the secondary voltage changes approximately linearly with variations of field imposed upon the primary cores extends from about 0.1 to 0.9 gauss. As the magnitude of the earth's field is in the range from about 0.3 to 0.8 gauss, and the changes which may be induced by a passing ship are a fraction of the earth's field, it is evident that the range avail-

able is well suited to this application. To have a relatively uniform response to change in magnetic field over as wide a range as possible, the detector is biased with a small compensating magnet to operate about a mid-point corresponding to a field of approximately 0.5 gauss.

Since the detector output is measured by the amplitude of the secondary voltage, the exciter-oscillator was developed to deliver a constant output in spite of normal variations in the d-c plate supply. The output from the magnetic-shore apparatus operates a test and firing relay in the corresponding mine. The relay is designated testing and firing because it performs two functions. (1) It energizes a small magnetic field about the Mu-metal cores, simulating an outside magnetic disturbance of fixed magnitude. The response on shore to this test field is a measure of the overall operation and sensitivity of the entire apparatus. (2) It conditions (or "selects") the mine to be detonated upon *simultaneous* application of a firing frequency.

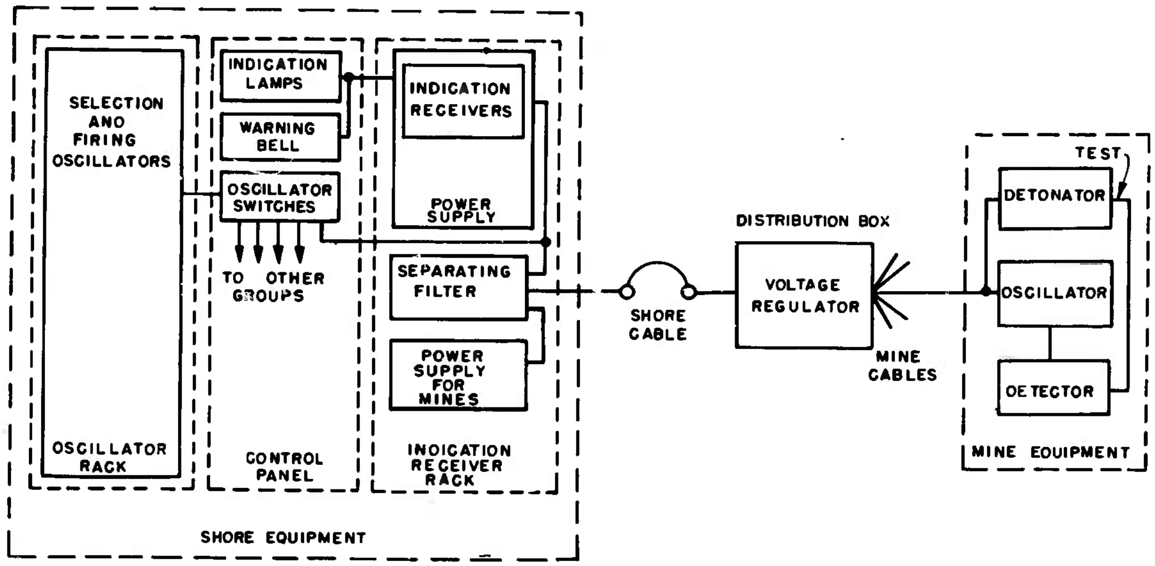


FIGURE 1. Functional diagram of shore and mine apparatus.

detector secondary goes to a detector-amplifier tube which modulates the output of an oscillator signaling back to shore. The oscillator is set to operate at one of the thirteen indication frequencies in the range from 2 to 10 kc, the particular frequency being specific to the mine in which the oscillator is installed. The oscillator output is coupled to the mine cable through a filter-amplifier which insures that no false signals can be impressed on the cable.

A selection and test frequency supplied from shore at the will of the operator may be applied to the detector. There are thirteen test frequencies between 250 c and 1,350 c, each assigned to a particular mine and receivable by that mine through a tuned filter. Impression of one of these frequencies on the mine cable from the

If a 200-c firing frequency (same for all mines) is supplied to a mine at the same time that the selection and test frequency is supplied, the mine will explode. A firing filter in each mine is tuned to accept the 200-c frequency. Thus, to explode a given mine, it is necessary that the test frequency specific to that mine be applied at the same time that the firing frequency common for all mines is applied. The achievement of a satisfactorily safe and reliable circuit which could not be actuated by any conceivable combination of accidental circumstances was most troublesome and is one of the most important accomplishments of the entire development.

In addition to the specific functions which have been mentioned, the mine apparatus in-

cludes an adjustment which corrects for any permanent change in magnetic field, such as might be caused by the tilting of the mine resulting from the explosion of a near-by mine. This correction process is fast enough to take care of natural or diurnal changes of the earth's magnetic field but is too slow to affect the sensitivity of the detector to changes caused by any normally moving ship.

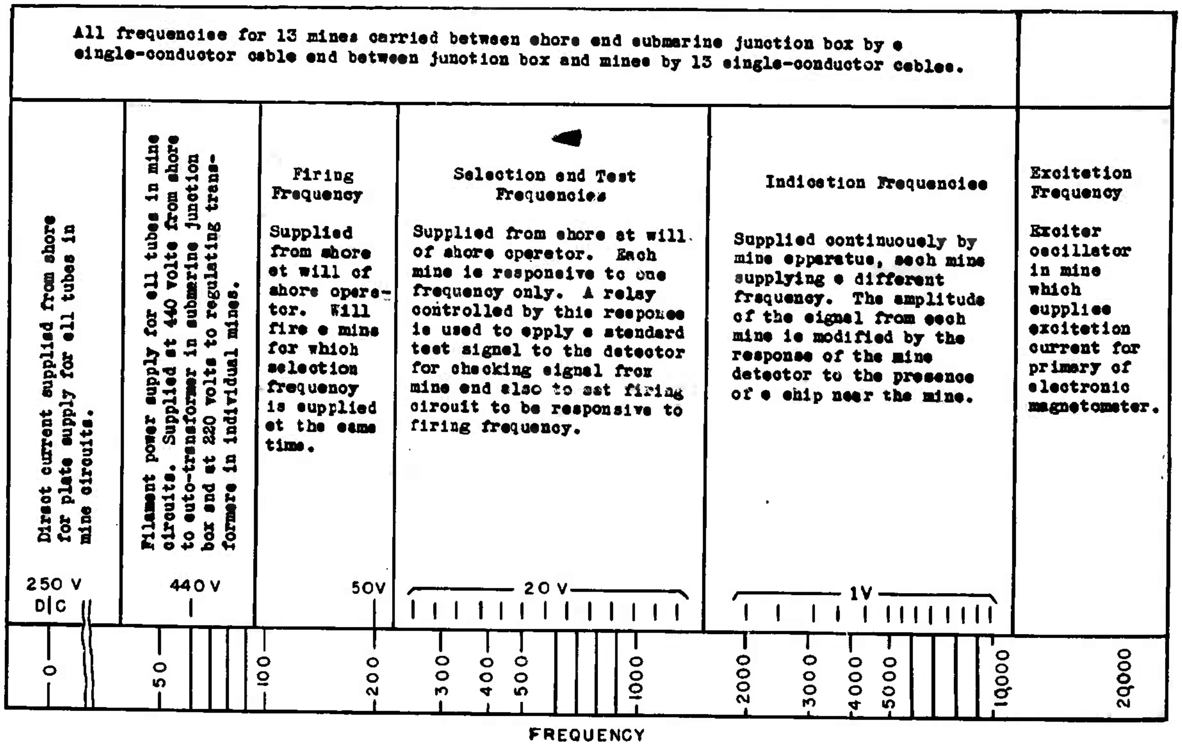


FIGURE 2. Frequency diagram for magnetic-influence submarine mine system.

The shore equipment consists of a power supply for the mines, selection and firing oscillators, indication receivers, the necessary filters, and a control panel.

For each cable there is a mine power-supply unit which supplies 250 v direct current and 440 v alternating current for the plates and filaments respectively of the ninety-one tubes in each group of thirteen mines. Power-supply voltages are effectively separated from each other and from the signal and selection frequencies by condensers and chokes in the mine apparatus. One set of thirteen selection oscillators and one firing oscillator supplies all units in the installation. Any oscillator is rendered operative by closing the appropriate oscillator switch on the control panel. The cable to which the chosen frequency is supplied is determined by closing the proper switch for testing detectors. The firing oscillator may be connected to any cable by closing the appropriate pull-type firing switch on the control panel.

A signal frequency from a mine oscillator, as modulated by the detector, comes in over the shore cable, is admitted by a filter to the appropriate indication receiver, is amplified and operates an indication light on the control panel. The amplifier also operates a single-stroke bell whenever any light goes on. Signals coming in on another cable operate similar apparatus and produce similar responses in another signal receiver and indicator unit.

A schematic diagram of a harbor-defense network involving ten units is shown in Figure 7. The general appearance of the main

indication and control panel for ten units is shown in Figure 8; and this figure also shows the panel indications for the hypothetical target of Figure 7.

Associated with each mine are two lights on the control panel which show the condition of the mine continuously. When the first light comes on, it indicates that a ship is approaching the mine; when the second light comes on, that the ship is close to the mine. With the activation of each light, a single-stroke electric bell

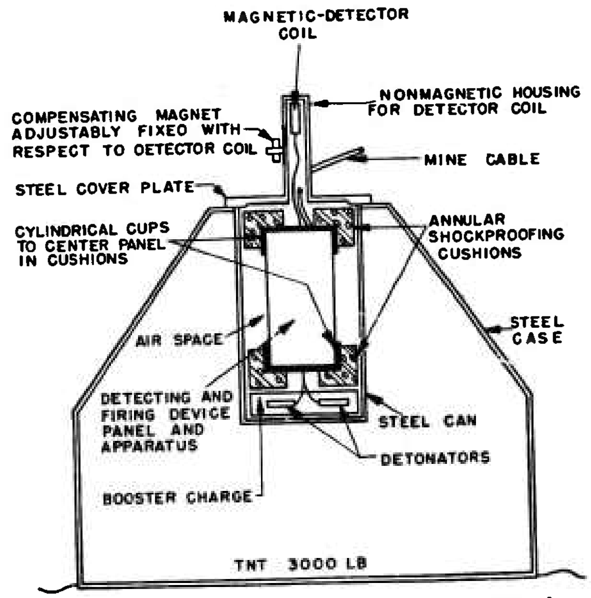


FIGURE 3. Arrangement of mine, magnetic detector, and associated electric equipment.

rings once. The first light serves as a warning signal; the second, as a firing signal. The progress of a ship following a specific course through a minefield is shown on the indication panel by the lighting of lamps associated with mines near enough that course to be influenced. An operator having such an indication and having also means to fire any one or any combination of mines could effectively control the fate of the vessel attempting to traverse the minefield. All signal lights on any row, corresponding to one shore cable and its thirteen attached mines, may be extinguished and all apparatus reset to operating condition by moving the switch at the right of that row to the "cancel" position.

To test a given mine, the operator closes the "unit selection" switch at the bottom of the column containing the mine (this energizes the oscillator supplying the frequency to that mine) and moves the switch at the right of the row containing the mine to the "test" position (this connects the proper mine cable to the selected oscillator).

If all apparatus functions, this test produces a signal back to the shore apparatus, which is indicated by the lighting of one of the lamps associated with the selected mine. The mine apparatus also contains a tilt indicator which, when the mine is seriously off level, modifies the mine circuit in such a way that a two-way impulse is sent back to the shore apparatus when the test signal is applied, so that both lamps are lighted instead of only one.

The mine is fired by simultaneous operation of the "unit selection" switch in the column containing the mine and of the special pull-type firing switch. This applies power to the oscillator operating at the test frequency of the mine so selected, applies power to the firing-frequency oscillator, and connects the firing and test frequencies to the mine cable. The simultaneous application of the test and firing frequencies operates two relays which fire the detonator and explode the mine.

The entire operation of the mine-control system described here depends upon the response of the mine detector to the magnetic field of a ship. The signal amplification available is sufficient so that if it is all used (by adjusting a variable gain control on the shore amplifier) the indication lights will respond to the noise level of natural or artificial changes in the magnetic field. The maximum sensitivity which may be used, therefore, depends on the magnetic environment of the location. In remote installations, far from artificial magnetic fields, a sensitivity approaching 0.1 milligauss for signal operations might be possible. None of the degaussing or deperming treatments of ships have reduced the fields so much that they are not appreciably stronger than the minimum at which the mine detector can be made effective. In fact, the degaussing treatment tends to be an advantage because it effectively restricts the response to the immediate neighborhood of the ship.

The pattern of the magnetic field below a ship is highly variable, depending on the ship, its magnetic history, and its heading with respect to the magnetic meridian and the magnetic latitude. For a degaussed ship the pattern may be quite irregular, with one or more positive and negative areas which, at depths of the order of 100 ft, have magnetic intensities of the order of 1 to 10 milligauss. Whatever the details of the magnetic pattern may be, the first change strong enough to affect the magnetic detectors will occur when the outer part of either a positive or negative area of the disturbance field passes over the mine. This change will result in the lighting of one of the indication lamps. As the ship moves on, the intensity of the magnetic field at the mine will continue to change in the same direction until the central part of that particular disturbance area passes the mine, whereupon the field will begin to change in the opposite direction. This reversal results in the lighting of the second of the indication lamps; in general, this occurs when the ship is relatively close to a mine.

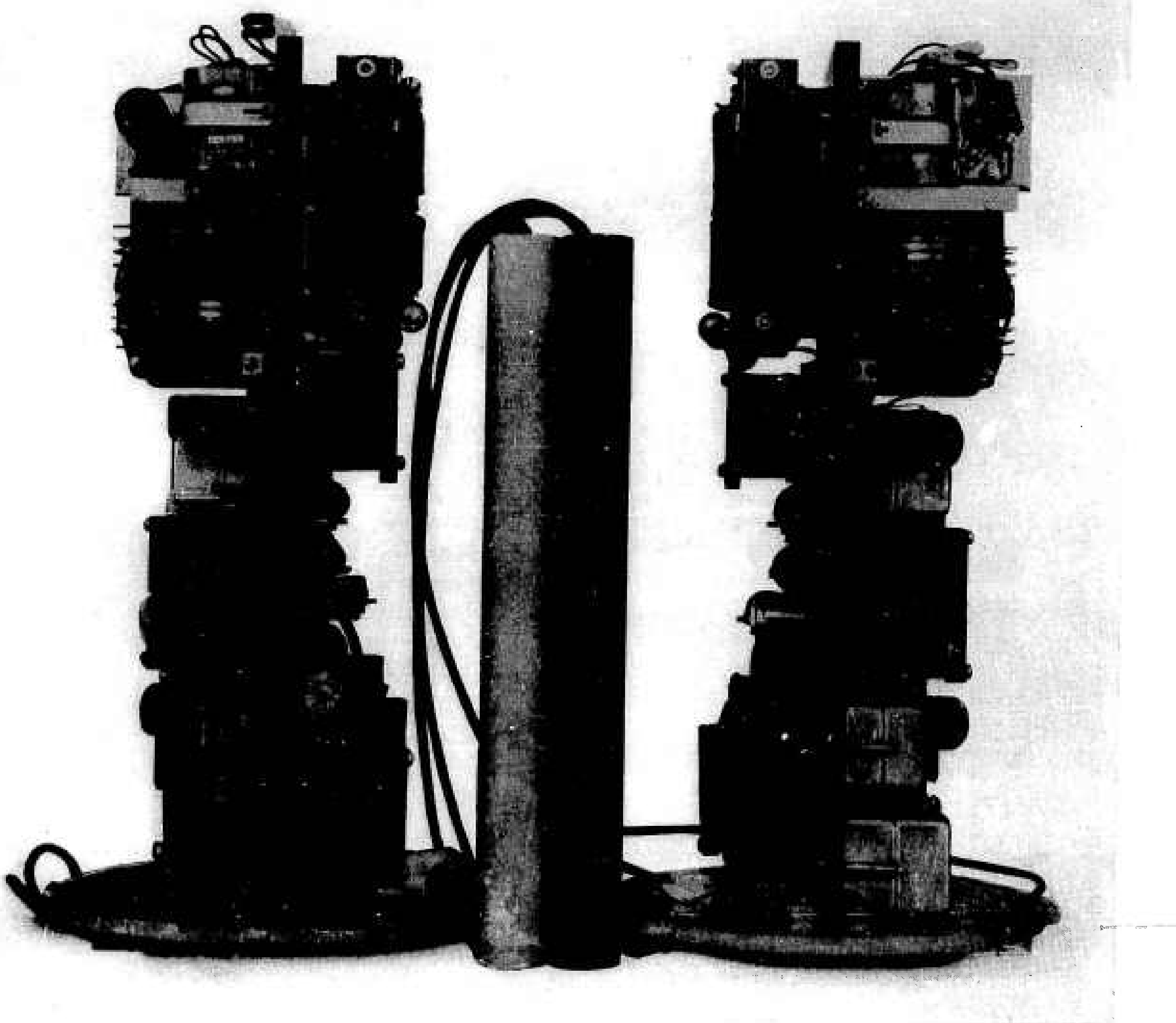


FIGURE 4. Complete assembly of mine apparatus and magnetic-detector coils.

Thus the first light serves as a warning that a ship is approaching the mine, and the second that it is close, and the mine should be fired then if the ship is to be destroyed.

In early test apparatus, a pen recorder was used to record the magnetic-field-intensity indi-

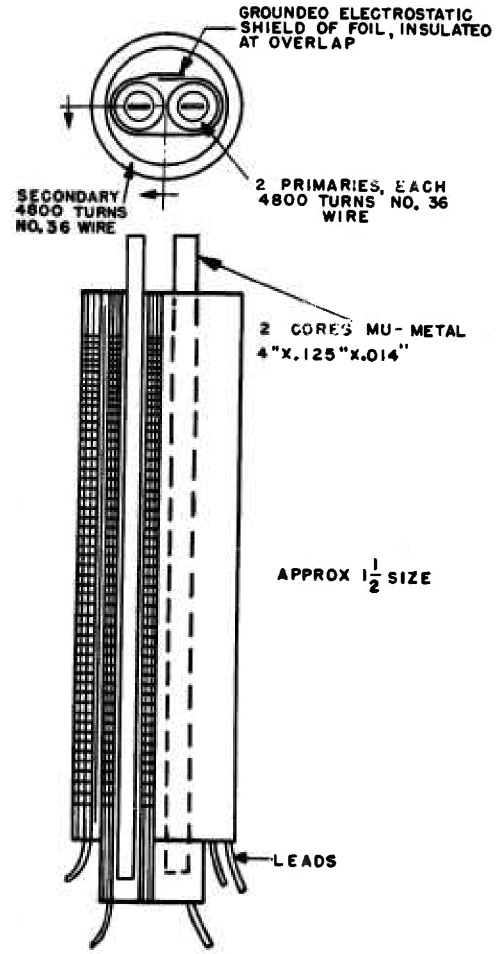


FIGURE 5. Magnetic-detector coil.

cations transmitted to shore by the equipment for certain types of vessels. Some of these are shown in Figure 9. The time scale (running from left to right in all cases) is the same for all the records, and so, roughly, is the magnetic-field scale. The dashed lines indicate coincidence of the bow and the stern of a ship with the line of sight from the control point to the position of the detector. The courses of the ships were not exactly normal to the line of sight and the ships might have been on either side of the mine and possibly out of the danger zone. The crosses on the records show the time of flashing of the indication lamps.

It is fallacious to base the firing of the mines on a predetermined field strength because mines will then blow up far ahead of strong targets. Use of time delays is also objectionable because, if they provide appreciable improvement of firing action on large, slow targets, they will permit fast ships to slip through. Firing at the point where the magnetic field reverses is somewhat better because the ship's field never reverses at great distances. However, a ship's signature may fail to reverse, especially if it is not degaussed. Accordingly, the firing-indicator arrangement used is so designed that reversals are created where they do not actually exist.

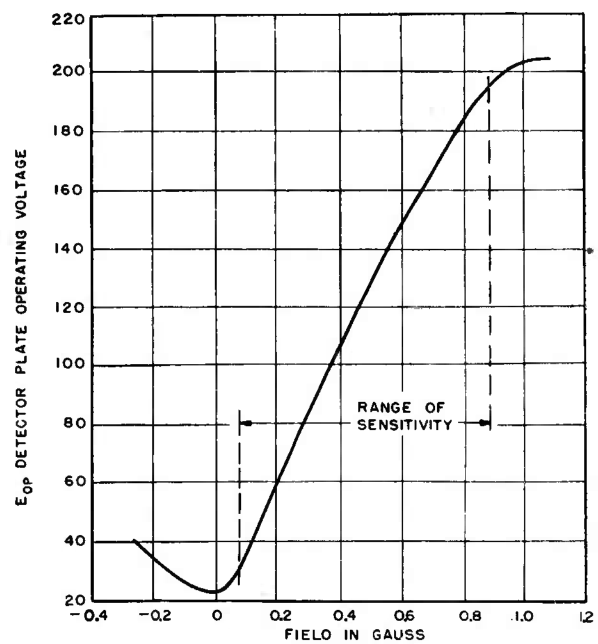


FIGURE 6. Magnetic-detector characteristic.

For a schematic diagram of the complete final magnetic mine unit (except for the firing circuit) see the Gulf Research final report.[14] For diagrams and pictures of the mine detonator circuit and the shore apparatus see the final report[4] of the Union Switch and Signal Company.

4.4.2 Control System with Sonic Detector

Paralleling the development of a magnetic detector, a 15-kc listening-type detector unit was developed for use with the control circuits.[22, 23] The military requirements placed on the performance of the sonic detector by the Submarine Mine Depot have already been listed (Section 4.2).

The first of these requirements (specifying the cone of influence) could not be realized in the device designed for the Depot; nor could it be realized for any other acoustic firing device designed for continuous operation on a controlled mine system and suitable for immediate production. A compromise was made in order that a number of units could be built without delay. In the listening unit a directional hydrophone is used; it is this feature which gives the mine its cone of influence and satisfies the first requirement within the limits consistent with the necessary simplicity for a controlled mine unit. The second requirement (actuation at sound pressures less than 500 bars) is easily satisfied.

A number of other features, though not specifically requested, were suggested as very desirable. Irrespective of the acoustic firing device in the mine, it should be possible to check from shore the overall sensitivity of the electric circuit in the mine. Changes in the plate power-supply voltage of ± 5 v should not affect the operation of the device, nor should transients in the line. The device should be so designed that any adjustment in the circuit that may become necessary because of aging may be made on shore. The circuit should contain a minimum number of tubes, and it is a great advantage to use the same type of tube throughout the entire circuit. All these useful features are incorporated in the final design of the sonic detector.

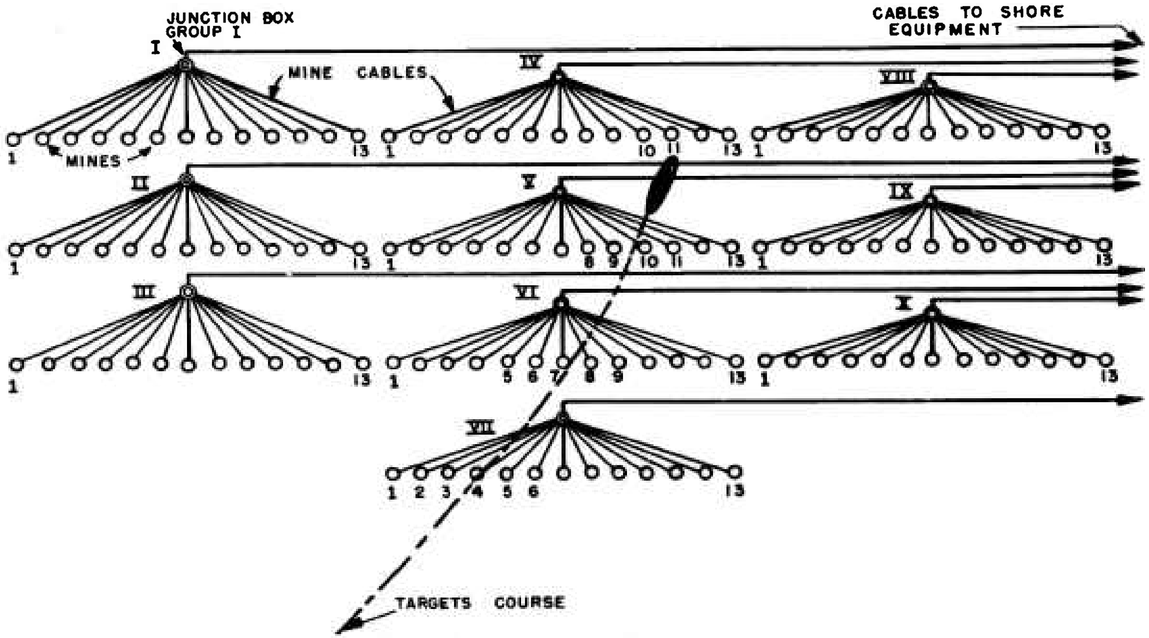


FIGURE 7. Shore-controlled minefield.

The sonic development may be summarized as follows. The unit has but one microphone, and it may therefore be classed as a one-channel system. There is only one amplifier whose gain needs checking, and this may easily be done from shore. With a one-channel system, the decrease in amplifier sensitivity with age may be compensated for by means of a calibrated adjustment on the shore control equipment—the same control used for varying from shore

the sensitivity of the magnetic detector. The electrical features of the particular system used which contribute to its simplicity and stability are: (1) use of simple conventional circuits; (2) use of a single type tube (taken from the Army-Navy preferred list) for all tube positions; (3) ability to use all tubes which conform to the normal commercial tolerances without any special selection; (4) insensitivity to small changes in plate-supply voltage; (5) use of a time-delay circuit, which prevents spurious responses of the device to accidental individual transients.

Mechanically, the device makes use of the unit type of construction, parts which form substantially complete and independent systems being built on separate chassis panels. Each subassembly is designed for mass-production methods and individual testing, servicing, and interchanging.

The block diagram for the apparatus at the mine is shown in Figure 10. Circuit diagrams and pictures of the equipment are given in the contractor's report.[7]

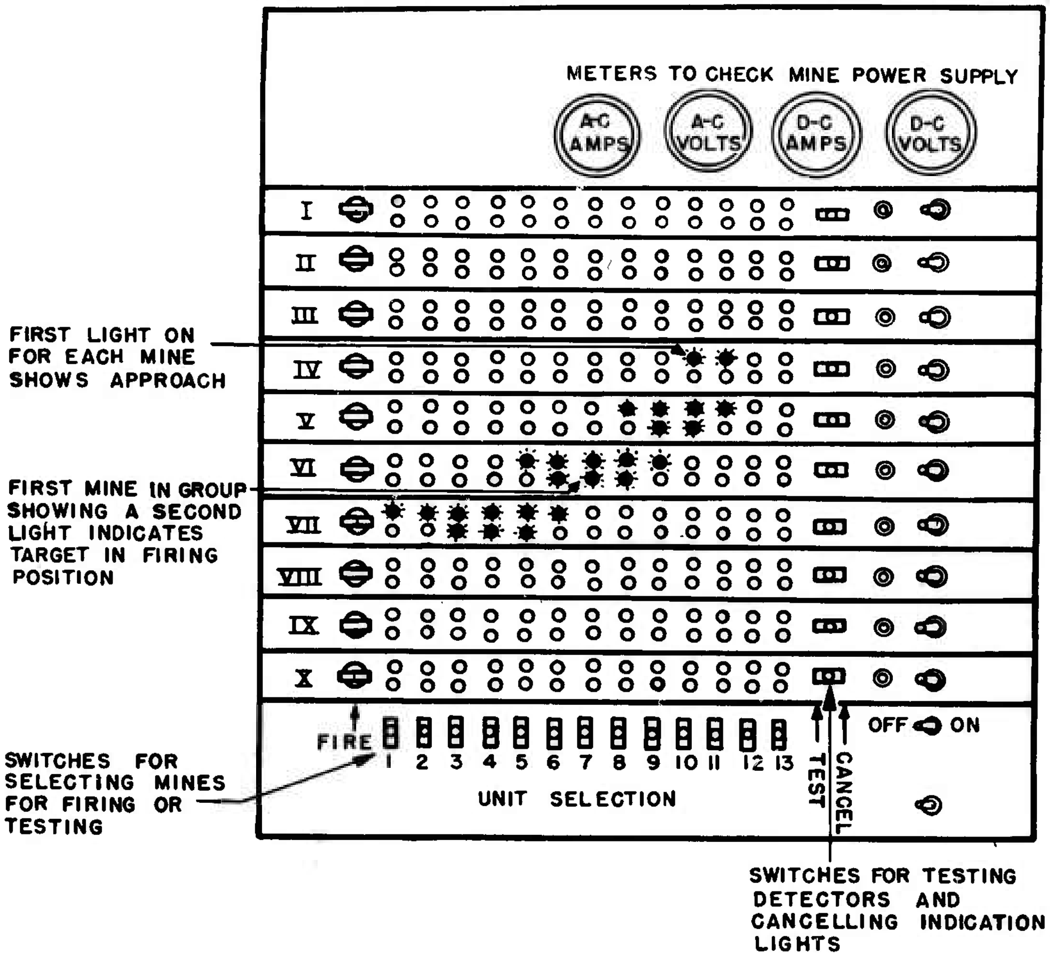


FIGURE 8. Control panel for ten units.

For a number of reasons it was desirable to listen at a frequency of 15 kc. A hydrophone (microphone) commercially available from the Brush Development Company has a beam pattern of about 45 degrees at 15 kc, as shown in Figure 11. This hydrophone (type AX-26-1)

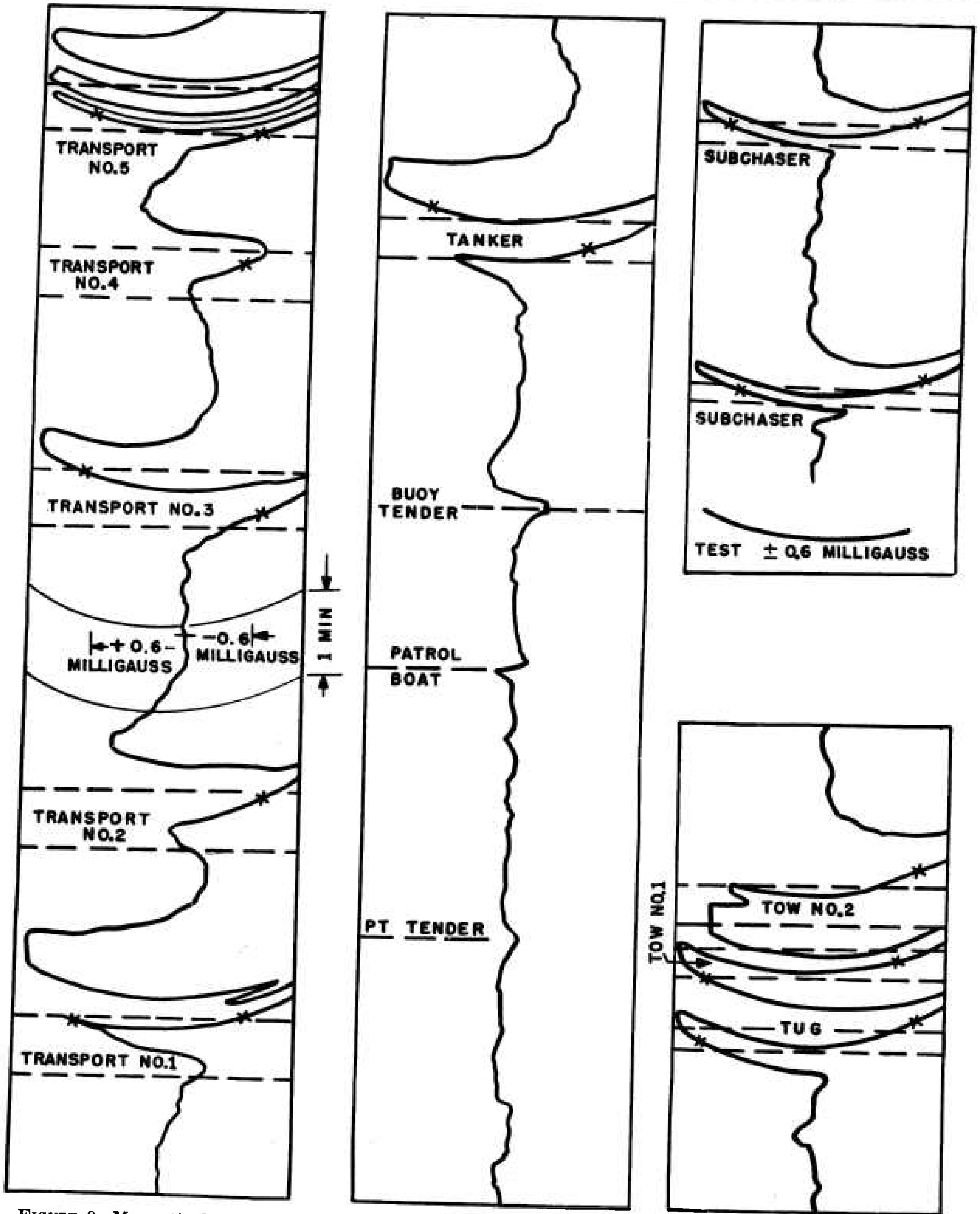


FIGURE 9. Magnetic-field-intensity indications transmitted to shore by the mine equipment for various types of vessels.

is used as the detecting element. It is mounted on top of the mine case so that the axis of the cone of sensitivity is vertical. It provides an electric voltage for the amplifier input which is proportional to the noise incident upon it. This voltage is then amplified and tuned (i.e., only voltage produced by noise in the range of 15 kc is amplified). The amplified voltage goes to the detector tubes, which provide a d-c output proportional to the 15-kc input. The oscillator generates a signal of the particular frequency assigned to the mine. The modulated amplifier provides variable amplification of the oscillator signal—an amplification proportional to the d-c voltage output of the detector. Noise picked up by the microphone therefore produces a variation in the signal-frequency voltage output which is sent from mine to shore. If the voltage variation of the signal frequency exceeds a specified amount, the indicator circuit operates at the shore control panel, and a warning is given.

Power is sent from shore to the unit, and alternating separated from direct current by a set of filters. The testing and firing relay is arranged so that when it is closed by the application of its appropriate frequency from the shore, an additional pair of contacts in the relay completes a circuit designed to supply a 15-kc calibration signal of known voltage. A calibration of the overall electric circuit is obtained by noting the change in signal-frequency voltage produced by the calibration signal.

It should be noted that with the magnetic-influence detector the operator is warned of the approach of a ship before it reaches the mine. In the case of a single-microphone detector no advance warning is given; the operator must be prepared to fire as soon as he sees the indication, or risk being too late and missing the boat (in every sense).

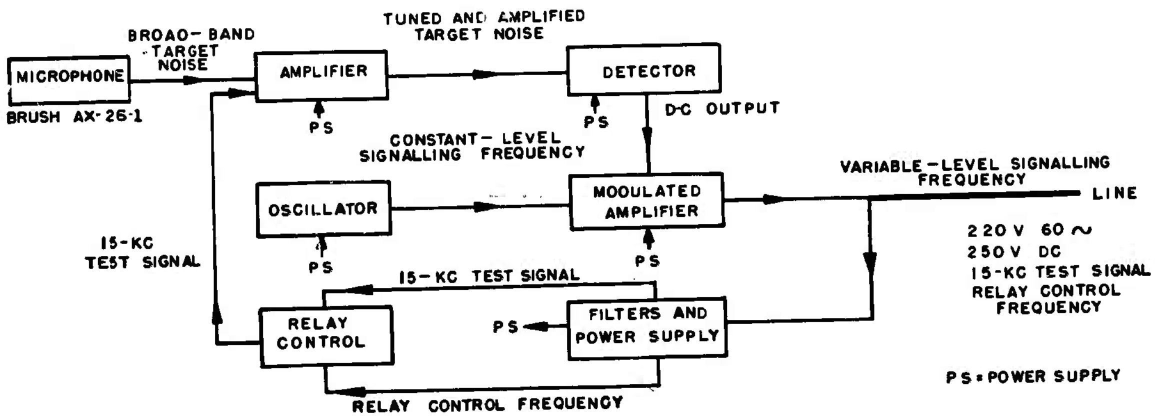


FIGURE 10. Block diagram of sonic detector and associated mine equipment.

4.5 HISTORY

4.5.1 Control System

The final control system as described above is the result of various developmental advances made on the problem.[4a] By March 1942, a new control system for use with influence-type mines was completed and delivered to Fort Monroe. This system provided for semi-automatic control of two groups of thirteen mines each. It was tested with the magnetic detectors during the beginning of April, but the detectors proved too erratic and further development was necessary.

By May 1942 some new circuits for a fully manual-control system and a very much simplified fully automatic-control system were developed. The mine equipment had been further developed. It was tested at the beginning of

May and found to be far less erratic, but not sensitive enough. Methods for increasing the sensitivity were suggested. Part of this improvement was to be made in the mine equipment and part in the indication receiver used on shore. Cathode-ray tubes were suggested for the shore equipment to indicate the behavior of the mine equipment. Listening devices for indicating the presence of a ship were introduced. It was during this time that the officers at Fort Monroe decided that fully automatic operation was not worth while and chose fully

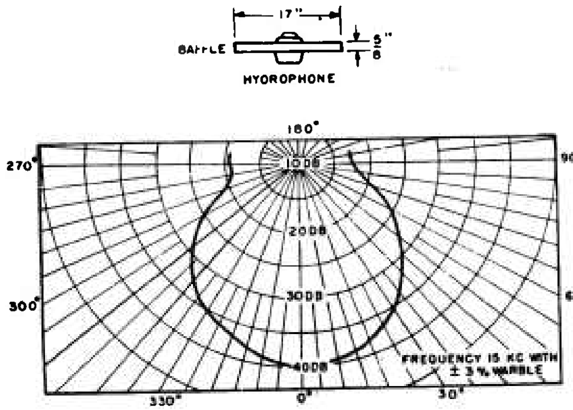


FIGURE 11. Directional characteristic of Brush Model AX-26-1 Hydrophone mounted in baffle shown. (Testing distance—30 in.)

manual equipment for controlling and firing the mine.

During June and July a simplified manual-control system was built for two groups with thirteen mines in each group. The new indication receivers were provided with a sensitivity adjustment, and the cathode-ray tubes were added to indicate the behavior of the detectors. Four of the magnetic detectors were provided with acoustic listening-type devices with the hope that both magnetic and acoustic indications could be obtained from the same mine.

Tests on this equipment were conducted during the latter part of July. During the period from August to October 1942 additional magnetic firing devices and indication receivers were constructed.

The tests conducted at Fort Monroe showed the merits of the control system and at the same time uncovered many minor faults which were gradually eliminated. As the behavior of the detector unit improved, the desirability of the cathode-ray tubes disappeared; early in 1943, it was decided to abandon them altogether and to depend entirely on indication lamps. A number of tests and demonstrations of this equipment were made, including the exploding of detonators. Ships entering the harbor were observed when they crossed the minefield where these experimental mines were located. Much information was obtained, showing that the magnetic detector operating with this frequency-control system gave very good results on all types of vessels, especially on the smaller ones.

4.5.2 Magnetic Detector

The present magnetic units are the result of a great deal of similar developmental work. The first two experimental samples of a magnetic detecting and firing device were tested at Fort Monroe in the summer of 1941.[7] This device sent to shore a signal of constant amplitude, variations in the frequency of which indicated magnetic changes at the mine. The sensitivity of the device was more than adequate, but it had many shortcomings. The exciting oscillator lacked stability; although apparently satisfactory when new, its behavior became progressively worse with aging. Firing indications were effective only about 50 per cent of the time. Part of the trouble was due to high sensitivity plus the noise level, part to blocking of the amplifier circuit, which would upset the detector for many minutes after passage of a strong target. Another limitation of the device was that it required a separate conductor for each mine.

The variations in firing indications observed with these detectors were attributed to the magnetic patterns of different ships as well as to shortcomings of the original apparatus. Accordingly, data on the magnetic fields of ships were obtained and efforts made to produce improved detectors. A new unit, Set C, was delivered to the Submarine Mine Depot in November 1941.[14a] It required a heavy set of batteries for operation of the detector and

seemed obsolete shortly after completion, in view of the possibility of greater flexibility offered by the frequency-control system which was being developed separately. In December 1941 a conference was held to coordinate work on the shore-control system and on the magnetic detectors. As a result, each was changed to suit the other; the changes improved both parts of the new combination. The control apparatus was actually simplified and improved in the process of incorporating a power source for operating the magnetic detectors; at the same time, it was made suitable for other types of detectors using vacuum-tube equipment.

By May 1942, 26 detectors, called Test Set D, were delivered in major part for use with the frequency-control apparatus.[8, 9] The detector was powered entirely by direct current from shore. This was a big step forward. However, in spite of improvements in the oscillator, the detector was still subject to gas-tube noises because gas-tube regulators for plate-supply voltage were used in each mine. These proved unsatisfactory because their voltages would occasionally jump a fraction of a volt, which was sufficient to give false indications. The detector oscillator was prone to fluctuate at times due to the cold-cathode gas-tube oscillator used. It was therefore decided to abandon cold-cathode gas tubes. This was made possible in succeeding models by progress in the frequency-control equipment which allowed ample 60-c power to be transmitted to the detectors to supply heater power for a-c tubes.

Test Set E was the first unit to use a-c tubes throughout.[10] A 2050 exciting oscillator tube was used, with great improvement over the cold-cathode tube. A vacuum-tube surge suppressor replaced the noisy gas-tube regulators, and a limiter circuit was added to improve firing characteristics and recovery time from disturbances. Two of these units were made, and one was delivered to the Submarine Mine Depot in July 1942. A similar type of unit, Test Set F, included provision for acoustic and magnetic reception from one unit, using one carrier frequency to convey both signals.[10] The magnetic signal provided the usual slow modulation of the carrier, but the acoustic device provided modulation in faster rates in the neighborhood of 240 c. The two rates of modulation were separated by dual shore receivers so that separate indications were obtained. Four of these units were delivered in July 1942 for tests at Fort Monroe. The combined acoustic-magnetic detectors operated satisfactorily, except that very strong magnetic signals blocked the acoustic signals and very strong acoustic signals shifted the points at which magnetic indications occurred.

To cut down the peak current in the 2050 oscillator, a revised circuit was developed. Units with this oscillator were designated Test Set E2.[11] Then this oscillator was replaced by a vacuum-tube oscillator, which was very much steadier, and a few other changes were made at the same time. The new type was called Set E2′.[11] Fifteen units built as type E2 and one built as type E were converted to type E2′ for delivery to the Submarine Mine Depot late in November 1942.

Set E2′ was superior to all previous types, but still had a source of occasional noise. At that time the set was redesigned to eliminate all the troubles that had been found and to incorporate Army-Navy preferred tubes. This new design was designated Test Set E3.[13] This was the final experimental design of which six were built and put on test in March 1943.

Through the entire development the principal difficulty was with noise. It is difficult to make sensitive circuits that will be completely quiet day after day in operation. Since the start of the development, circuits could be built and were built that would operate apparently with a very satisfactory noise level; but occasional bursts of noise occurred when they were run day after day on recorders, when tubes were replaced, or when circuits were duplicated in number. Gas tubes, the chief source of these troubles, were eliminated entirely from the detectors, and every other precaution was taken to achieve a high degree of continuous, quiet operation.

4.5.3 Sonic Detector

When the development of the acoustic detector was undertaken, four different methods of

detection were considered: (1) acoustic range finding, (2) listening-type control unit, (3) beam-type control unit, and (4) echo-type unit. The listening-type control unit has several outstanding advantages, such as simplicity, low power drain, ease of adaption to control system, and ease of combination with the magnetic firing device. In addition, it has the advantage that the only countermeasure against a minefield of such units would be to cross it on "hand" control. The echo-type unit had the advantage of being one of the few practical devices that did not depend on the output of sound from the ship. Hence, a submarine could not slip by it.

The first acoustic detector developed in this work was an echo-type unit.[21] In this development an acoustic signal of high-frequency sound is produced by a Rochelle-salt transducer (a device which acts either as a microphone or loudspeaker). The signal consists of a succession of pulses, each pulse consisting of high-frequency sound, approximately one millisecond in duration, occurring at a rate of about ten per second. After the transducer sends out a pulse it acts as a microphone. It hears an echo from the surface of the water and any other nearby reflecting object. However, the equipment is so designed that it is responsive only during a time interval which begins several milliseconds after the initial pulse and which ends shortly before the surface echo arrives back at the transducer. In order to be detected, an object must therefore come closer to the mine than a distance equal to slightly less than the depth of the water.

Two circuits were developed. The first was designed to operate on battery-type vacuum tubes; the second, on heater-type tubes, operating on alternating current made available at the mine. Two mine-control units of this type were put on continuous test at Fort Monroe.

The fundamental design of either circuit is the same. An oscillator tube drives the crystal transducer which produces the acoustic pulse. The transducer then acts as a microphone connected to the input of an amplifier. If an echo is received, it is amplified and detected. However, the detector tube is supplied with plate voltage only during the period in which the device is to be operative. During the operative period, if an echo is received, it raises the potential at the plate of the detector tube and also at the control electrode of a cold-cathode gas trigger tube which follows the detector. If a strong echo is received, the potential at the plate of the detector will become great enough to discharge the gas tube. This discharge supplies a large pulse to an integrating filter. If this happens a number of times in succession, the device sends an indication back to shore. Thus, isolated spurious echoes and line transients will not produce a shore indication.

Three types of transducers were considered when the project was started: (1) magnetostriction, (2) quartz crystal, and (3) Rochelle salt crystal. Of the three, the Rochelle salt crystal has the greatest sensitivity; as units of this type were available from the Naval Research Laboratory, they were used.

Two types of apparatus were tried for excitation of the crystal transducer. The first employed a Strobotron. The breakdown of the gas tube excited the crystal transducer. This circuit was economical in that the cold-cathode tube required no power for heating the filament. However, the characteristics of different tubes were not very uniform, and the operation of the circuit was not very stable; hence it was decided to try a Hartley-type oscillator employing a low-drain filament-type tube. An oscillator of the self-quenching type was used. Since the total power input to the Hartley-type oscillator was less than that for the Strobotron type, and since the former was found to be more stable and to give as much output as the latter, the Hartley-type oscillator was used in the final design of the circuit.

This detector did work and was being improved; but, for reasons already mentioned, it was decided to drop further work on it and to concentrate on the development of a listening-type device.

Some exploratory work had been done on listening devices at 250 c and at 100,000 c.[21] When work was started on the design of a listening-type device, the Submarine Mine Depot submitted the desired characteristics already mentioned. In order to approximate these with-

out too much developmental work, a listening frequency of 15 kc was chosen. A listening-type acoustic firing device was developed. This was installed for tests which proved its operation satisfactory. Subsequently the Submarine Mine Depot requested six more units for further testing. The Depot also decided to place a contract for a production quantity of this device.

Chapter 5

GUN RANGING AND LOCATING SYSTEMS

By *Frank Woodbridge Constant*

5.1 INTRODUCTION—SUMMARY OF RESULTS

This report contains a complete technical description of the work performed by the Division of Physical War Research at Duke University under its contract with OSRD. The body of this report is addressed to readers of the type represented by the technical men of NDRC and the technical officers and civilians of the Army and Navy.

Section 5.1 describes the organization of the project and summarizes its results. Section 5.2 presents the general background of the subject in order that the relation of each phase of the work to the whole may be better understood; it also includes a brief description of methods and equipment in acoustic gun ranging which were standard at the time the project was initiated. Section 5.3 covers the study and improvement of standard methods and equipment, and Section 5.4 deals with the development of new methods and equipment. These two sections describe the majority of the work undertaken, considered from two angles: (1) obtaining the necessary data and (2) handling the data after it has been obtained. Under each, first the methods and then the equipment required are discussed. Section 5.5 explains the main part of the physical research—a fundamental study of sound transmission through the atmosphere, with emphasis on those micrometeorological factors which produce fluctuations and irregularities in sound propagation. Section 5.6 discusses accessory projects and work of a general consulting nature. Section 5.7 gives the present status of the subject as a whole.

As each particular project is taken up in detail, a brief historical description of the earlier work is followed by a technical description of the final form of the apparatus developed or the conclusions reached. How well the Division succeeded in meeting specific military requirements is stated in each case.

More detailed descriptions of any phase of the work can be found by referring to the Bibliography at the end of the report.

5.1.1 Purpose and Organization[1]

Purpose. This project as a whole was concerned with the investigation of the detection and location of enemy guns, mainly by sound. Particular emphasis was placed on the location of enemy artillery.

The military importance of quickly locating enemy guns of all kinds made very desirable a fresh, coordinated attack on the problem. The fluidity of the military situation in World War II, in contrast to the relatively static front of World War I, added to the importance of the problem. The urgency of improved gun ranging was expressed repeatedly by the Field Artillery Board of the Army Ground Forces during the course of the work.

The project originated with Section C5 (later Section 17.3) of NDRC, whose chief was Harvey Fletcher. V. O. Knudsen, a member of this Section, was assigned as Supervisor of the project, which was later designated as No. 17.3-3. Fletcher and Knudsen, with W. S. Gorton, Technical Aide to the Section, visited the Field Artillery School at Fort Sill, Oklahoma, and the University of Oklahoma at Norman, Oklahoma, and then the Field Artillery Board at Fort Bragg, North Carolina, together with the University of North Carolina, at Chapel Hill, and Duke University, at Durham, North Carolina. NDRC wanted to locate the work near one of the above military reservations and at a university where the necessary facilities would be available. As Duke University seemed to meet these requirements best and expressed willingness to undertake the work, it was awarded an OSRD contract.[a] The

[a] Contract No. OEMsr-734.

Division of Physical War Research was set up at Duke University to operate under this contract, which was later supported by the Army Control No. SOS-13 and Navy Control No. MC-100.

The activities of the Division began at Duke University officially on September 15, 1942, under the directorship of J. P. Maxfield. Space was allocated in the Physics Building. The personnel grew steadily: on January 1, 1943, the scientific and technical staff numbered thirteen; on August 1, 1943, it numbered twenty-three and later totaled thirty.

In order to familiarize the Division of Physical War Research with the methods and systems of gun ranging by sound and with the problems to be solved, members of the Division were invited to attend conferences with military personnel. Existing methods of acoustic gun ranging were discussed and their shortcomings pointed out. No specific requirements were given at the start of the work. The Division was asked to consider the subject as a whole and to investigate possible improvements in existing methods and equipment, as well as the feasibility of introducing new methods or systems. In general the two main requirements to be kept in mind were increased accuracy and increased speed of operation.

Organization. The work was organized and proceeded along four main lines: (1) the development and improvement of existing methods and equipment, (2) the study and development of new methods and equipment, (3) physical research on the fundamental principles of sound propagation and sound ranging, and (4) general consulting work for the Armed Forces.

The physical research group was concerned with the fundamental principles of sound ranging. Its work thus included a study of sound-ranging methods in use or under investigation, as well as a study of the best methods of handling the data obtained from any of the systems being developed. This group also served the Division in another manner: its members, by keeping familiar with the work of the Division as a whole, were available for consultation in regard to the fundamental principles of the various projects being developed by the engineering groups. Instances arose where a problem begun under the physical research group reached such an advanced stage that it became a development project and was classified as such. As a consequence, some results of immediate use were produced, new methods and equipment were developed for future use, and a background of fundamental information necessary for long-term development work was obtained.

As work along the above lines progressed, it became possible for the Field Artillery Board to request the Division to push specific projects that seemed especially promising or of fundamental importance. Then, as particular pieces of equipment were developed, the Field Artillery Board and (through an extension of the original contract) the Marine Corps Equipment Board, Quantico, Virginia, assisted in subjecting the equipment to a series of field tests. As a result of these tests the Armed Forces recommended specific alterations and improvements, so that the equipment in its final form would meet their military requirements. In this connection it should be mentioned that the Field Artillery Board, the Field Artillery School, and the Marine Corps Equipment Board were always most cooperative and helpful. Relations with these groups were mutually cordial and friendly.

The Armed Forces gave many indications not only of the importance they attached to the work, but also of their satisfaction with its progress and their continuing confidence in the Division. For example, in the case of the Dodar, an earlier model (D-2) was tested by the Field Artillery Board. It added a few military requirements to the functions of the original and then recommended the adoption of the Dodar even before the new model had been designed and tested. After the new model had been completed, orders were received for over 90 instruments of the new type, mostly for combat use. Arrangements were made for the manufacture of these instruments on a "crash procurement" order.

In general, the Division was granted, when necessary, the highest priorities for procuring equipment. Finished instruments were in several cases flown to the fighting fronts. On one

occasion Mr. Maxfield was flown by Army bomber to England to consult with British scientists and military personnel. Without such support and cooperation from the Armed Forces it would not have been possible for the Division to have accomplished nearly as much as it did in the way of supplying the Armed Forces with new instruments and information.

Further evidence of the success of the Division in meeting military requirements is to be found in reports received from the fighting fronts which describe the behavior of certain instruments developed by the Division and subjected to actual combat use.

5.1.2 Standard Methods and Equipment in Sound Ranging

Obtaining the Data

Methods. A study of the straight base and comparison with other types of bases showed that the standard straight base adopted in World War II was the most advantageous for the type of fluid warfare generally encountered.

Equipment. (1) *The modified T-21-B microphone.* An acoustic coupler (MX-346/PN adapter) was developed for the T-21-B condenser microphone employed in the standard gun-ranging equipment (GR-3-C). This coupler extends the frequency response of the T-21-B microphone from 25 to 60 c, thereby improving the character of the records obtained with it by giving a sharper initial break, permitting some identification of gun sizes, and making recognition of the ballistic wave much easier. The modified microphone is also less susceptible to moisture. Modification parts were turned over to the Field Artillery Board and to the Marine Corps Equipment Board and were later flown to the fighting fronts. As a result of this work the Field Artillery Board included a similar extension of frequency range in the military requirements of the T-23-T5 hot wire microphone.

2. *The dry paper recorder.* An investigation was made of the possibility of replacing the standard photographic method of recording with one employing a wax paper or a paper of the Teledeltos type. This was found possible, and a model using wax paper was developed. Elimination of photographic recording makes unnecessary the use of the chemicals and supply of water called for in a developing process. This is a great advantage in either hot, dry climates or in very cold climates. When it was found that a similar instrument, based on identical principles, was being developed under a Signal Corps contract, efforts were turned in other directions.

3. *The binaural outpost.* A binaural outpost listening device designated Binop was developed and demonstrated. Such a device offers the possibility of eliminating the outpost observer in the standard gun-ranging method.

Handling the Data

Methods. (1) *Standard plotting and methods of weighting.* An investigation was made of the possibility of reducing errors in location by improving the methods of evaluating the data. It was found that intersections of asymptotes resulting from sub-bases one sub-base length apart, i.e., alternate asymptotes, are most reliable. The relative reliability of other intersections was also evaluated.

2. *The analytical method of computing.* A straight computation method was developed for determining the location of an enemy gun from the data obtained by the standard method. In this method the coordinates of the gun's position are computed with formulas and the help of prepared tables. This method has the advantage of eliminating the plotting board normally employed in the standard method.

3. *The nomographic method of computing.* Nomograms which use standard sound-ranging data and give both azimuth and range in a single setting were developed. Nomograms were computed for the cases of the 2- and the 4-sound-second base with all microphones operative, and for the case of the 4-sound-second base with an inner microphone inoperative, two nomograms being necessary to take care of all possible situations in this last case.

4. *The ballistic-burst method.* A method was developed for locating a gun from the record of the shell-burst and ballistic waves only. Such a method is useful when meteorological or other conditions are such that it is difficult or impos-

sible to identify the muzzle blast of any particular gun. This method may also be employed to check the position determined from the gun wave when the shell-burst, ballistic, and gun waves are all recorded.

The first step in this method permits the determination of the line of flight of a projectile from a record of its ballistic and shell-burst waves. The Field Artillery Board has approved this step and the Field Artillery School has issued an Appendix to Field Manual FM 6-120 covering its use in the field.

The second step in this method permits determination of a range term. The range calculated by this method was generally found to have an error from 2 to 5 per cent of the total actual range, due to variations in the muzzle velocity of the shell. These variations may be due to faulty powder charge or to wear on the tube of the gun.

5. *Study of meteorological corrections.* A comparison was made of several methods of correcting for the effect of meteorological conditions on the estimated position of the sound source to be located. Application of the standard meteorological correction method adopted by the U. S. Field Artillery for a straight base was found statistically to improve the results considerably, although the effectiveness varied considerably in individual cases. Results, based on a rather small amount of data obtained from actual artillery fire, indicated more elaborate methods to be little, if at all, superior to the standard Field Artillery method.

Equipment. (1) *Trace-reading templates.* A transparent template was developed to assist in reading from the record on the photographic tape the corresponding time of arrival of a sound-wave impulse at a given microphone. This template makes it possible for enlisted personnel to read traces with a much improved accuracy since personal judgment as to the point of break is eliminated. Over 800 copies of this template were furnished the Field Artillery Board, and some were flown to the fighting fronts.

2. *Nomogram and accessories.* Satisfactory prints on a semiopaque plastic of the computed nomogram were manufactured. A mounting device for effecting the required settings and readings in the field was constructed, permitting rapid and accurate use of the nomogram.

3. *Artillery plotting grids.* The Field Artillery Board expressed a need for plotting grids having greater dimensional stability than that provided by the paper sheets then in use. Previous experience with nomograms made it possible to satisfy this need. Several grids printed on Lucite, and special indicators which can be attached to the grids by means of vacuum cups were produced, as well as other accessories. These plastic grids provide greater stability and accuracy.

4. *Ballistic-burst templates and tables.* In connection with the ballistic-burst method mentioned above, 100 sets of templates and the necessary time interval and range tables for obtaining the range term were manufactured and delivered to the Field Artillery Board for shipment overseas. These templates applied to the German 170-mm K18 and 210-mm Mrs 18 guns. In addition, templates and tables were prepared for the American 155-mm M-1 gun; these are to be incorporated into the Field Artillery School instruction course and manual covering the ballistic-burst method.

5.1.3 New Methods and Equipment in Sound Ranging

Obtaining the Data

Methods. (1) *The seismic method.* A study was made of the possibility of detecting and ranging artillery by means of surface seismic waves. Previous work by the Signal Corps indicated the impracticability of using deep-traveling refracted and reflected seismic waves. The use of purely surface earth-borne waves was investigated with no practical results.

2. *The doppler effect method.* An investigation was made of the possibility of developing a method of sound ranging in which use is made of the doppler effect. This was also found to be impracticable.

3. *The multiple-short-base method.* An investigation was made of the possibility of developing a method of sound ranging employing several short, two-microphone bases, suitably coordinated. Such a method was found to

possess definite advantages to contribute to the mobility and speed of operation of the sound-ranging system.

Equipment. (1) *The Dodar.* The development of new, lightweight, sound-ranging instruments for use in the multiple-short-base method was carried to completion. This equipment, which has been designated Dodar (Detection of Direction and Range), includes as its principal element an electronic time interval measuring device. In operation, one Dodar unit yields a direction line to the sound source; when three units are used, a triangle of intersections is obtained from which the location of the sound source is obtained. Field tests indicated that enemy artillery could be located at ranges up to 8,000 yd (and in some instances up to 12,000 yd), within an accuracy of 200 yd, and that a properly trained team could determine a gun location within one minute after reception of the sound signal.

Twenty-five units of the first experimental model of the D-2 Time Interval Dodar were manufactured, at the request of the Marine Corps Equipment Board. Of these, twenty units went to the Marine Corps for trial under combat conditions, and one unit went to the British. An improved model, known as D-3 (U. S. Signal Corps AN/PNS-1), was next developed at the request of the Field Artillery Board. One hundred units of this model were manufactured. The Dodar was placed in operation by the Marine Corps during several campaigns; reports on the Iwo Jima campaign indicate it was effective under battle conditions. Technical manuals covering the Dodar have been issued by the Marine Corps and the Army.

2. *The lightweight crystal microphone.* As an important adjunct of a complete Dodar system, a new ultralightweight microphone for sound ranging was developed. This microphone employs a crystal element capable of withstanding temperatures exceeding those likely to be encountered in the field. It weighs about 4 lb and is considerably less bulky than the present T-21-B condenser microphone. Provision is made for quickly altering the frequency-response characteristics to permit the microphone to be used either with Dodar or with the standard sound-ranging recorders. The smaller size reduces the time and labor of installation.

Handling the Data

Systems of Coordination. Consideration was given to the best method of coordination to use when employing the Dodar system. It was concluded that this could best be determined by actual combat experience, and the decision was left to the Marine Corps.

Probability of Gun-Location Errors. A theoretical method was worked out of evaluating the probability of locating a target within 200 yd when two direction lines with their angular errors and the spacing between their origins are known. The calculated results were put in graphical form. Actual errors observed during field tests with Dodars agreed well with those calculated.

Reduction of Errors Due to Meteorology and Terrain. During the experimental tests of the Dodar sound-ranging system, effects due to meteorological and terrain factors were observed. Methods were sought to reduce these errors. A simplified form of the standard meteorological correction used by the Army Field Artillery Observation Battalion was adopted for reducing steady wind and temperature effects. Attention was called to the effect of fluctuations in meteorological conditions (the "met") and the need for further study of this subject, particularly in connection with short sub-bases. Terrain effects were found to be minimized by proper location of the microphones.

5.1.4 Fundamental Study of Sound Transmission through the Atmosphere

The physical research was concerned chiefly with a fundamental study of sound transmission through the atmosphere, particularly along a boundary such as the ground. It was realized that the major inaccuracy in acoustic gun ranging is caused by the effects of meteorology and terrain on the sound during its transmission from the source to the detecting equipment. Therefore, the possibility of reducing errors of this type was continually kept in mind, first through an empirical investi-

gation of the possible relationships existing between the errors and such meteorological measurements as could be made, and second through a basic, long-term physical study, both experimental and theoretical, of sound transmission through the atmosphere.

Investigation showed that meteorological errors fall into two classes: (1) those due to overall and slowly changing conditions (the "macromet") and (2) those due to meteorological factors which vary rapidly and in a random manner (the "micromet"). Particular attention was given to the latter, and special micrometeorological equipment was designed. Both steady, single-frequency sources and impulse sources were used in a statistical study of the relationship between the amplitude of a sound wave and its time of arrival under varying conditions; certain interesting correlations were obtained.

The effect of terrain was also investigated. Although this work yielded no results of immediate applicability to gun ranging, it indicated the possibilities of high-altitude listening for enemy troop movements, etc. Furthermore, a theoretical hypothesis of the propagation of sound along a boundary was developed which checks data at higher altitudes, where existing theory and experiment agree, but which is also in closer agreement with data at lower altitudes and grazing incidence than are existing theories.

5.1.5 Accessory Projects

Binaural Listening. In connection with the development of the binaural outpost, a small-size binaural listening system for detecting enemy equipment was developed. This system gives some information as to the direction from which noises are emanating. It may be considered as a highly portable anti-infiltration warning device.

Analysis of Field Records. Gun-ranging film records and data sent from the fighting front were analyzed for the Army Ground Forces. In several cases the analysis yielded quite different diagnoses from those which were obtained by inspection in the field. As a result, specific recommendations were made about obtaining and analyzing combat data.

Proposed Method of Sound Ranging Eliminating "Met" Corrections. A new method of sound ranging employing a two-dimensional microphone array was proposed and developed analytically. This method was shown to have application: (1) as a practical field method of sound ranging without the use of meteorological corrections, (2) as a research method for investigating the effective major meteorological structure for sound ranging, and (3) as a research method for investigating the effect of fluctuations in the meteorological conditions upon the accuracy of sound ranging.

Sphinx. A preliminary attempt, terminated by the ending of World War II, was made to detect and locate caves by sonic means. Field experiments in which an M-1 rifle was fired 40 ft in front of a 3-ft cubical box indicated that it was possible to detect reverberations set up in the box 50 to 100 ft in front of the opening to the box. Subsequent tests on full-size caves with commonly available explosive sound sources did not yield a positive result, but indicated that sound sources with much higher energy content in a frequency range below 50 c were required to excite the reverberation and resonant frequencies of such caves sufficiently to be detectable.

General Consulting. Considerable consulting work on specific problems was carried out for the Armed Forces throughout the life of the project. Every effort was made to render such service as useful as possible. In a sense the whole project could be viewed in this light. In all phases of the work, close liaison with the Armed Forces was maintained. One valuable by-product was the education of military personnel in the principles and operation of their sound-ranging equipment, enabling them to put it to more effective use. The liaison officers for the Armed Forces indicated that this alone made the project well worth while, even if no new equipment had been developed.

5.2 LOCATION OF ENEMY EQUIPMENT BY SOUND

The various projects undertaken by the Division of Physical War Research were all related

and covered all aspects of acoustic gun ranging. In order to understand the purpose of each phase of the work and its relation to the whole, the particular problems faced and the results achieved, it is necessary to be familiar with the general background of gun ranging.

5.2.1 The Standard Method[26]

Under the above heading will be described the standard method and equipment employed by the U. S. Field Artillery Observation Battalions before and at the time of our entry into World War II. This method received its main development in World War I; since then certain modifications, mainly in equipment, have been introduced to improve the results.

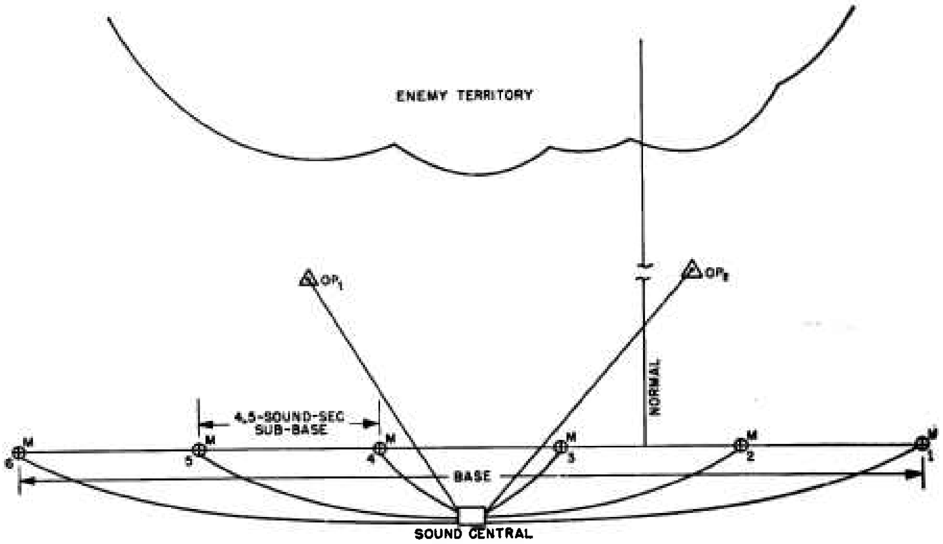


FIGURE 1. Typical sound-ranging installation.

Basic Theory. A typical sound-ranging installation is shown in Figure 1. The discharge of a gun or burst of a shell causes a sound disturbance, or vibration of the air, lasting for only a fraction of a second. The impulse so produced is propagated through the air in all directions at the same speed as any other sound, 360 to 380 yd per second at average air temperatures. In still air, the sound will arrive at two given points at the same time if their distances from the source are equal—that is, if the source of the sound lies on the perpendicular bisector of the line connecting the two points. For a source in any other position, the arrival times at the points of observation will be different. This difference increases as the source location moves away from the perpendicular bisector, and thus provides a measure of its angular displacement from this line. If two microphones are placed some distance apart and the difference in arrival time of a sound at each microphone is recorded, the direction of a ray which passes very close to the origin of the sound may be determined. Other combinations of two microphones will provide similar rays, and from their intersections the source of sound may be located.

Sound Base. In practice, a sound wave is detected by an array of four to six microphones, normally spaced at equal intervals (700 to 2,000 or more yd) along a straight line or, under certain conditions, along the arc of a circle. However, they may be spaced at unequal intervals along a straight or broken line. Such an array is termed a sound-ranging base or sound base. A straight-line segment connecting a pair of adjacent microphones constitutes a sub-base. Normally, sound-ranging installations are accurately surveyed in.

Recording. Each microphone is connected by a wire or radio circuit to the recording set located at the sound central. The sound impulse received at each microphone is recorded by this

equipment on a moving paper tape; these recorded impulses are called breaks. In front of the sound base, at distances of from 1,000 to 2,000 yd, one or two outpost observers (OP_1 and OP_2) are stationed. Either observer, upon hearing the sound of a gun or shell burst, must actuate the sound-ranging apparatus in time to record the sound.

Oscillograms. The oscillogram is a paper tape upon which a time scale (1/100-second intervals) and the arrivals of sound impulses are recorded. The time of arrival at each microphone, as measured from an arbitrary zero time, is read from the oscillogram, and the difference between arrival times is computed for each pair of adjacent microphones.

Plotting. On the plotting board, the mid-point of each sub-base is plotted and the perpendicular bisector is constructed for use as a reference line. A ray toward the sound is drawn from each mid-point making an angle θ with the reference line, as determined by the relation:

$$\sin \theta = \frac{t}{s};$$

where t = the distance between times of arrival at the two microphones, in seconds;
s = the distance between microphones in sound-seconds.

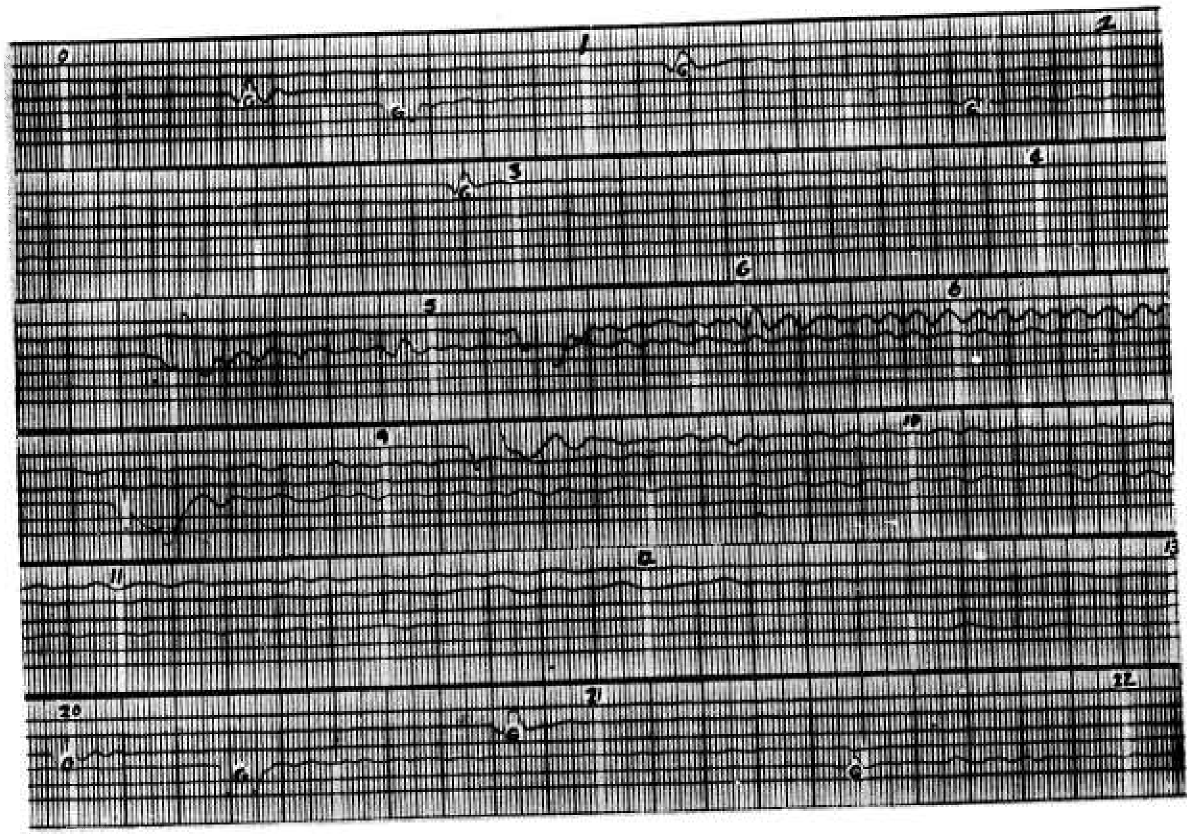


FIGURE 2. Sample galvanometer record for a six-microphone base, taken by U. S. Army in France.

One sound-second, the distance sound travels in 1 second in air under accepted standard atmospheric conditions, equals 369.2 yd. The intersection of the plotted rays (or average intersection of a polygon of error) is an approximate location of the source of sound. A more accurate location is obtained by applying curvature and weather corrections to the measured time intervals.

Number of Microphones. The number of microphones installed depends on available time and terrain. A complete installation normally employs five or six microphones. A minimum of four microphones should always be installed to permit three-ray intersection at the target. Increasing the number of microphones increases the number of intersecting rays and improves the reliability of locations. There is also the possibility of one or more microphones becoming inoperative.

Comparison of Bases. The most important advantage of a regular base (microphones uniformly spaced) is that the recorded arrivals of sound at the microphones form an easily recognized pattern on the oscillogram. Another advantage of a regular base is that standard plotting equipment with previously prepared time scales may be used. The curved regular base avoids the possible error of plotting a sound source to the front when it is actually to the rear, and facilitates oscillogram reading, because the recorded sound arrivals are grouped more closely together than for a comparable straight base. The curved base requires more computations in survey than does a straight base, and survey of a curved base is often more difficult to accomplish. This base was thus well adapted to the static fronts in World War I, but it was replaced in World War II by the regular straight base, which can be set up and used more quickly. Two such bases may be set up at right angles to each other, using one microphone in common. The irregular base is used when the terrain or time available for survey does not permit the installation of a regular base. It results in irregularity in the sequence of breaks, which, when there is considerable artillery activity, may render the oscillograms unreadable.

Length and Location of Base. The unit of measure for sub-bases is the sound-second. Convenient sub-base lengths for rapid installations are 2 and 4 sound-seconds. However, other values, preferably multiples of a standard length, may be used. Satisfactory results may be obtained if the base length is not less than one-third of the range. The radius of a curved sound base is the distance in sound-seconds from the center of curvature to the arc through the mid-points. A radius is selected which will place the center of curvature near the center of the area to be observed, or which will fit the base onto the available terrain. A base should be as close as possible, consistent with the proper location of the outpost observer, to the area to be observed, and so oriented that the perpendicular bisector passes through the approximate center of the area.

Outpost Positions. One outpost position should be at least 2 sound-seconds (approximately 750 yd) closer to a sound source than any microphone. After the outpost observer detects the sound, some delay, due to his reaction time, occurs before he depresses the starter key; there is a further delay in the operation of the relays before the sound set begins recording. For a short base, one outpost position may be sufficient. For a long base, two outposts, one toward either flank of the base, are necessary for complete coverage of a wide front, unless a single observer can be placed well forward.

Sound Central. To reduce the amount of wire necessary, the sound central should be as near the center of the sound base as is consistent with security. Concealment for the personnel at the sound central and a covered route of approach should be provided. It may be desirable to install a sound base in which some or all of the wire circuits are replaced by a radio sound-data transmission system.

Reading Oscillograms. Oscillograms are obtained by recording sound arrivals either electrically or photographically on a paper tape, at a rate of approximately 6 in. per second. On the tape, a number of horizontal lines are traced, one corresponding to each microphone installed. When no sound or wind strikes a microphone, the corresponding galvanometer trace is recorded as a straight line. Wind causes the line to waver from its normal position. When the sound of a gun reaches a microphone, an electric impulse is communicated to a galvanometer, producing a wavy line or break (see Figure 2). The point at which the trace first departs from its straight-line path, or zero line, is the initial break. With sound-ranging equipment now in use, the initial break is always downward for a sound beginning with a compressional wave, such as is produced by a gun

or bursting shell. In photographic recording, oscillograms are taken from the oscillograph, completely developed, and partially fixed. The fixing process may be completed by additional immersion for a few seconds in appropriate chemicals. Records may be read while wet, then dried for subsequent file. Both the galvanometer traces (horizontal lines) and the timing lines (vertical lines), as well as a serial number and the photograph of a 24-hour clock are recorded photographically on the oscillogram. The distance between adjacent vertical lines represents 0.010 sec. With this scale as a basis, the oscillogram reader determines the time of the initial break for each trace. Seconds, tenths, and hundredths are read directly, and thousandths are estimated by interpolating between the dots or lines. Recording equipment which is sufficiently sensitive to the higher frequencies may record a ballistic wave, which can readily be distinguished from a gun wave. Equipment less sensitive to higher frequencies may record the same sound, in which case the trace may be mistaken for that of a gun wave. Experience with a particular design of equipment will enable the observer to determine into which class the trace falls. The relative amplitudes of recorded gun and ballistic waves do not agree with their relative loudness as heard by an observer and may be misleading to an oscillogram reader.

Theory of Sound Plotting. The discharge of a gun or burst of a shell causes a pressure disturbance in the air which may be visualized as a constantly expanding hemisphere, with its center at the origin of the sound. If there is no wind, and the entire mass of air has a uniform temperature of 50 F and uniform relative humidity of 50 per cent, the velocity of the advancing wave front is 369.2 yd per second. These are the assumed "standard" conditions used in sound ranging. If it is assumed that the gun and all microphones are in the same plane, and the time readings for two adjacent microphones M_1 and M_2 (see Figure 1) are T_1 and T_2, then the time difference $(T_2 - T_1)$ multiplied by the velocity of sound in air V equals the difference in distances traveled by the sound from the source to each of the two microphones, $V(T_2 - T_1)$. Since by definition a hyperbola is the locus of all points the difference of whose distances from two fixed points is constant, the sound source lies on a hyperbola whose foci are the two adjacent microphones M_1 and M_2 and whose constant difference in distance is $V \cdot (T_2 - T_1)$. A hyperbola constructed from these values would pass through the sound source. A hyperbola constructed with M_2 and M_3 as foci and $V(T_3 - T_2)$ as fixed difference would also pass through the sound source. The intersection of the hyperbolas constructed for all pairs of adjacent microphones is the location of the sound source, but the physical construction of so many curves is impractical in sound ranging. Associated with each hyperbola is its asymptote. At ranges normally encountered in sound ranging, the hyperbola and its asymptote are only a few yards apart, introducing only a very small or negligible error. The construction of the asymptote may be simply and rapidly performed for each time difference between adjacent microphones with the aid of a transparent fan, marked with a time scale for the particular base employed. In practice, after an approximate value for the range has been determined, a curvature correction for each subbase, called the asymptote correction, is found by use of a chart.

Weather Corrections. The methods described assume standard weather conditions, which seldom exist. To account for actual weather effects, corrections are applied to time intervals measured under existing conditions to determine the intervals that would be recorded under "standard" conditions; rays are then plotted using the corrected intervals. In the standard method, correction formulas for wind and temperature are used. These formulas are based on physical principles, but involve the assumption of a horizontally stratified atmosphere and the so-called effective uniform wind and the effective temperature. If the effect of humidity is also to be compensated for, the so-called virtual temperature is used. The effective wind speed is an empirically determined average of the wind velocities at various levels as measured by balloons observed with theodolites. The effective wind direction is similarly determined, and the effective temperature is arbitrarily taken as 2 F below that at the ground surface.

Polygon of Error. Even with accurate survey and complete curvature and weather corrections, a point plot (all rays of the sound plot intersecting at the same point) is seldom obtained, principally because exact weather corrections cannot be made. The polygon bounded by the intersecting rays is termed the polygon of error, which, when evaluated, determines the probable location of the sound source. Unless the polygon is very large or time is available for a more careful evaluation, this is accomplished by inspection. When the polygon is not evaluated by inspection, a unit weight is given to the intersection of any two rays; this simplifies procedure but does not take into account relative strength of the intersection. If a grid has been placed on the sound plotting board, the coordinates of the probable location of the sound source may be read off directly.

Accuracy of Location. The estimated accuracy of the location is the number of yards that the determined location of the target is estimated to vary from its true location. The accuracy of a sound-ranging location is somewhat better in deflection (measured from the perpendicular bisector of the base) than it is in range (measured along the perpendicular to the base). Thus, a reported accuracy of 50 yd may represent a possible error of 50 yd in range, but only 20 to 30 yd in deflection.

5.2.2 Sound Waves Associated with Gunfire

General. There are several distinct sounds associated with artillery fire, some or all of which may be produced when a single round is fired. Of these, only two, the gun wave and shell-burst wave, are of general use in sound ranging. A third, the ballistic wave, may have occasional use.

Gun Wave. The gun wave, or muzzle wave, is the sound produced by the piece when it fires. Gases under high pressure suddenly released from the muzzle create a pressure wave. The shape of the wave front is initially quite complicated, but after the sound has traveled a short distance, the wave front becomes very nearly spherical, with its center of curvature a few yards ahead of the muzzle. Most of the energy of this sound is in the lower audible and subaudible frequencies. The wave form is smooth and, in general, the larger the gun, the longer is the period of oscillation.

Ballistic Wave. A projectile whose velocity in flight is greater than the velocity of sound gives rise to a ballistic wave, or shell wave, analogous to the bow wave of a ship. The presence of a ballistic wave is apparent to an observer near the line of flight of the shell because two distinct sounds are heard. The first, a sharp crack, is the ballistic wave. The second, a lower pitched boom, is the gun wave.

Burst Wave. The burst wave, or detonation wave, is also an impulse wave, which originates in the bursting of a high-explosive shell. It is similar in some respects to the gun wave, but results from a violent detonation rather than from explosion of a slow-burning propellent charge. The energy of the detonation is distributed over a wider range of frequencies. If sound-recording equipment is sensitive to higher frequencies, a more jagged record is obtained at short ranges. Because of greater attenuation of high-frequency sound, however, a record of a shell burst at a long range is almost identical in form to that of a gun wave.

5.2.3 General Requirements of the Project

The study and improvement of standard sound-ranging methods and equipment involved practically every phase of the system. Methods of obtaining and handling the data were improved. In the development of new methods and equipment attention was given to the need for sound-ranging equipment better adapted to invasion tactics and a more fluid type of warfare. Finally, the need for reducing errors in sound ranging caused by weather and terrain was responsible for fundamental physical research on sound transmission above the ground.

5.3 STANDARD METHODS AND EQUIPMENT IN SOUND RANGING

5.3.1 Obtaining the Data

METHODS

Types of Bases.[2] In choosing the best type of microphone base, many factors must be con-

sidered, such as ease of survey, number of microphones and amount of wire available, mobility, ease of camouflage, type of recorder used, ease of identifying sound sources on the record, ease of calculations, method of meteorological correction, and resulting accuracy.

1. Curved Base. A curved base of circular form was used by the U. S. Army in World War I. This base requires more time to set up than a straight base, but once established it possesses certain advantages. For example, the symmetry is such that from a quick inspection of the arrival times at the various microphones one can estimate the general location of the enemy gun relative to the center of curvature of the base.

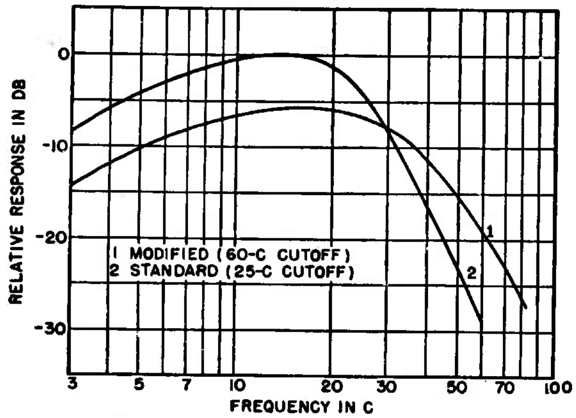


FIGURE 3. Frequency-response characteristics of the T-21-B microphone and the GR-3-C recorder.

2. Straight Base. The circular base was replaced in World War II by a regular straight base. This type of base can be quickly surveyed in. Ease of plotting is another factor in its favor, but a quick estimate of the location of the enemy gun from inspection of the arrival times is less feasible than with the curved base.

3. Triangular Base. The U. S. Signal Corps suggested and developed a sound-ranging system employing triangular sub-bases,[27] in each of which three microphones are placed at the vertices of an equilateral triangle. This arrangement gives better directional characteristics, and computed azimuths are independent of the velocity of sound and hence independent of the effective wind and temperature. A physical rather than an empirical method of correcting for the macromet was worked out for this base. Disadvantages are: the difficulty of identifying identical sound sources at the two isolated triangles or the necessity of coordinating the two triangular sub-bases to range on the same sound impulse; the more difficult surveying job; the increased amount of wire required; and the fact that if one microphone goes bad, the base becomes inoperative. To counteract the first objection, a combination of the triangular and straight bases was suggested by the Division for those cases where time and amount of wire available permit, e.g., on static fronts.

It is found that different methods of applying a meteorological correction may be used for each type of base. These methods will be compared later. It was first assumed that, after corrections had been applied, the probable error in arrival time at each microphone due to the combined effect of all factors was the same for each type of base. The resulting error in location was then investigated. Under these circumstances it was found that a single triangular array is superior as a direction finder to a two-microphone array with the same separation, and that a combination of two triangular bases gives a more accurate direction-and-range determination than a three-microphone straight base if the product of the length of a side and the separation between the centers of the triangles is greater than the square of the microphone separation along the straight base. In general, either an increased number or wider separation of microphones results in increased accuracy, and a two-dimensional array is more accurate than a one-dimensional setup.

EQUIPMENT

As explained in Section 5.2, the standard system of gun ranging utilizes a long, straight microphone base, one or two outpost observers, and a photographic recorder located at the sound central. Efforts of the Division were directed toward improving all three elements of the standard system.

Modified T-21-B Microphone.[6] This study of microphones was undertaken to determine those characteristics of the standard sound-ranging microphones which would produce maximum ease of trace reading and maximum differenti-

ation of wave shape. The subjects investigated were: (1) the characteristics of standard sound-ranging microphones used in conjunction with standard recording devices; (2) the effect of microphone response characteristics on the recorded wave; (3) the relationship between microphone response characteristics and extraneous sounds, and their effect on the wave; (4) modifications of standard microphones to obtain the greatest amount of information possible from the record.

Standard sound-ranging microphones. The microphone most widely used in sound-ranging operations in 1942 was the T-31-B.[28] This microphone was intended for use with the GR-3-C and similar sound-ranging sets. It is a combination condenser microphone and amplifier, mounted in a cylindrical container which forms a two-section, unterminated acoustic filter with damping built into each section. The overall amplitude-frequency characteristics of this microphone and the recorder are shown in Figure 3, Curve 2. (The recorder alone shows a response curve with a maximum at 20 c and a response down 6 db at 2 and 80 c.) A frequent source of equipment failure encountered with the T-21-B microphone under field conditions is in the condenser element, where the spacing between the diaphragm and stator plate is only 0.004 in. The entrance of moisture or particles of dirt causes the element to become erratic. Repair of microphones so damaged is difficult.

Effect of apparatus response on gun record. The range and magnitude of frequencies present in gun waves have been investigated by Kelley.[29] Representative values are shown in Table 1, which also includes data on the ballistic wave, and on the shell-burst wave associated with each major artillery piece. The frequency of maximum sound energy received varies with range, terrain, and meteorological conditions, but Table 1 shows clearly the advantages of a system having a response extending to a higher frequency than does the response of the standard system with the T-21-B microphone (see Figure 3).

Limitation due to noise. The extraneous noise encountered in field operations is principally caused by wind, but may also result from aircraft, vehicles, etc. Wind noise is of a random nature and is not confined to any narrow band of frequencies, although the strongest components are at low frequencies. Noise from aircraft and vehicles in general increases with frequency in the region from 25 to 100 c and higher. These considerations impose an upper limit to the response a gun-ranging microphone should have.

TABLE 1. Frequencies of sound waves produced by guns.

Gun	Muzzle Wave		Ballistic Wave	Shell-Burst Wave
	Frequency (c) of maximum energy component	Frequency range (c) less than 6 db down from max.	Frequency (c) of maximum energy component	Frequency (c) of maximum energy component
105-mm M-2 How.	40	15- 80	90	18
155-mm M-1 How.	20	5- 40	32	15
8-in. M-1 How.	16	6- 28	46	12
240-mm M-1 How.	13	6- 19		
4.5-in. M-1 Gun	20	5- 40	120	20
155-mm M-1 Gun	12	4- 25	94	17
.30-cal Mach. gun	150	50-350		
.50-cal Mach. gun	120	50-250		

Modification of the standard microphone. As a first step in raising the upper cutoff frequency, new filter plugs were substituted, extending the response to 35 c. To raise the upper cutoff frequency still higher, an acoustic coupler tube was developed (see Figure 4). This adapter seals the condenser element against the entrance of moisture and dirt by substituting a tube for the outer filter chamber and plug of the T-21-B; incorporated within the tube is a thin rubber

diaphragm which effects the seal. The high flexibility and low mass of this diaphragm permit sound pressure to be freely transmitted to the condenser diaphragm. At the same time the rubber diaphragm provides mechanical loading of the acoustic space to raise the response to 60 c. The inner filter plug of the T-21-B is replaced by a suitable plug at the base of the tube. The desired frequency response is obtained by choosing suitable values for the diameter and thickness of the rubber diaphragm, the diameter of the tube, and the hole dimensions of the lower filter plug. As a further means of preventing any appreciable amount of moisture from reaching the condenser element, a desiccant chamber is provided. The air trapped between the rubber diaphragm and the condenser can breathe through small holes to an outer chamber enclosed by a thin rubber bellows. Incorporated in the modification is a method of securing a frequency-response characteristic having a high-end cutoff at 100 c. This is intended for special use, such as mortar or machine-gun locating, and may be obtained by the removal of a screw from the center of the lower filter plug of the acoustic coupler tube.

Advantages of the modified microphone. For purposes of comparison, the overall frequency-response characteristics of the modified and standard T-21-B microphones, used with a GR-3-C recorder, were determined experimentally. In Figure 3 the results are shown for the modified (Curve 1) and the standard (Curve 2) microphones. The base of sound intensity is the same for the two curves. In further field tests a comparison was made of the wave shapes resulting when gun waves, ballistic waves, and shell-burst waves were recorded by the two microphones. Tests were also made to determine the effects of extraneous noises on each. The following conclusions were reached:

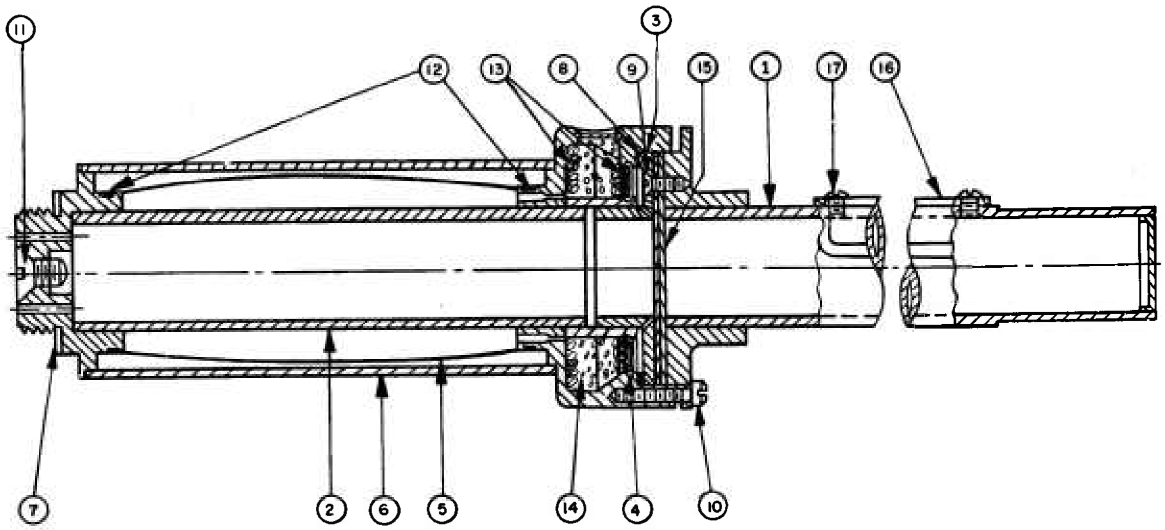


FIGURE 4. Acoustic coupler tube.

1. The optimum overall amplitude-frequency response of the microphone and recording apparatus combined should have an upper cutoff of about 60 c for ranging on field artillery weapons, and of about 100 c for arms of smaller caliber such as machine guns.
2. With a microphone having this 60-c response, a sharper break is obtained than with the standard 25-c response.
3. The ambiguity between ballistic and muzzle waves on the recorded trace is reduced by use of this higher cutoff response.
4. Indications are that the extended frequency response is useful in securing information as to the type of gun being ranged (i.e., small, medium, or heavy).

5. The increased amplitude of the recorded wave trace of all but the largest guns yields an improved signal-to-noise ratio, even though the response to extraneous noise is greater with the extended frequency range.

6. Although the peak sensitivity of the modified microphone is less than that of the standard, the wider range of response maintains the effective sensitivity to actual gun sounds.

7. The device used to incorporate a wider frequency response in the standard microphone reduces certain inherent faults and increases its operating life.

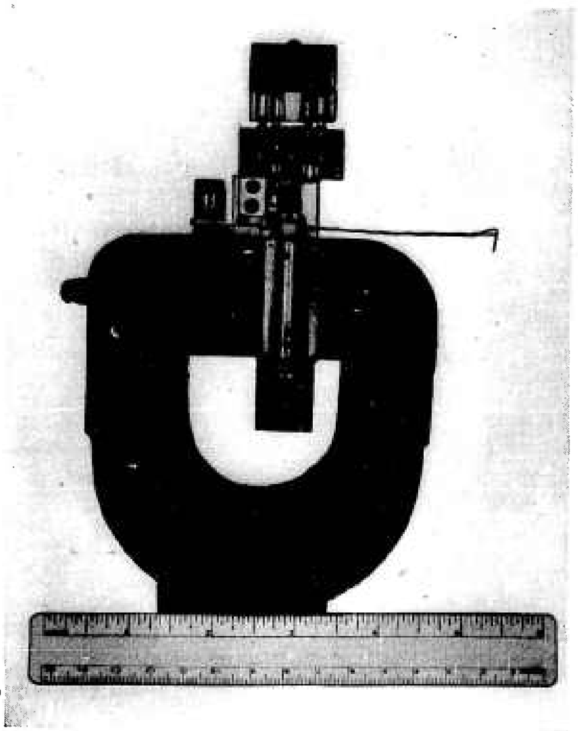


FIGURE 5. Galvanometer unit for dry paper recorder.

Dry Paper Recorder.[16] The purpose of this work was to investigate the possibility of replacing the standard photographic recorder of the GR-3-C with a small, lightweight, nonphotographic recorder employing a strip of paper or similar material. Portability was a feature particularly desired by the U. S. Marine Corps. In this investigation the development of two recorder systems was initiated. The first was intended as a replacement for the GR-3-C, and the second was requested by the Marine Corps for use in its anticipated sound-ranging operations.

1. *GR-3-C replacement.* A dry paper recorder to replace the GR-3-C sound-ranging set was developed to the stage of a satisfactory laboratory model; the work was carried far enough to prove the feasibility of the equipment. Further work toward its final design was in progress but was stopped when it was learned that the Signal Corps Laboratory at Fort Monmouth, New Jersey, was developing similar equipment under contract with the Cambridge Instrument Company.

A dry paper recorder using either wax-coated paper (furnished by Waxon-Carboff Company) or Teledeltos paper (distributed by Western Union Telegraph Company) was found practical. However, data available at the time this work was abandoned indicated that the wax paper was superior to the Teledeltos. The wax paper is rated to withstand a temperature of 125 F. The thinner grades were found to require less pressure for marking, and less friction was encountered when a heated stylus was used.

It was found possible to mount six or eight galvanometers side by side, and to give a trace of sufficient amplitude by employing a recording paper 3 in. wide. The final form of galvanometer unit developed (shown in Figure 5) was capable of being tuned to a natural frequency of 70 c. When so tuned, its d-c sensitivity was 0.033 in. per ma, and its response was essentially flat up to 30 c, with a 9 db peak at resonance. Damping was obtained both electrically and through the viscosity of the heated wax acting on the stylus.

Satisfactory heater-type pointers for marking on the wax paper were developed.

In developing a marking mechanism for the time scale, a 100-c tuning fork was used to drive a synchronous motor. With such a mechanism 0.01-, 0.1-, and 1.0-second identifying marks could be made on the paper. The project was completed before the mechanism could be perfected.

A paper drive mechanism, operated electrically at a rate of 5 in. per second, was de-

veloped in laboratory form. The final model of the GR-3-C replacement is shown in Figure 6.

2. *Marine Corps recorder.* A dry paper recorder which was even lighter in weight and simpler in operation and maintenance was developed for the Marine Corps to the stage of a laboratory model. Work was abandoned on notification from the Marine Corps that such sound-ranging facilities would be furnished

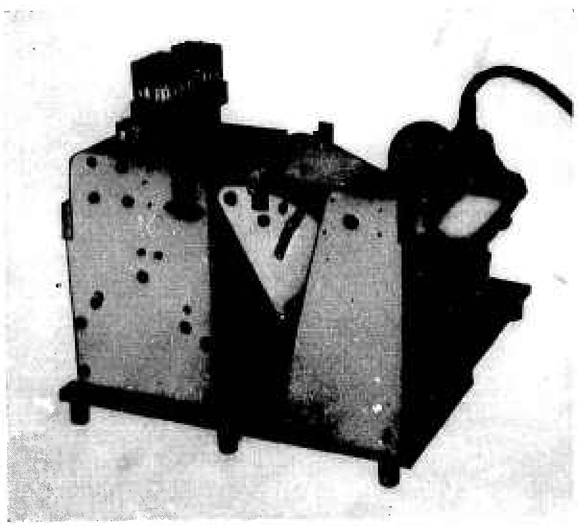


FIGURE 6. Dry paper recorder: GR-3-C replacement.

them by the U. S. Army Field Artillery Observation Battalion.

Teledeltos paper was used in this recorder. The marking was made through sparks from fixed pointers. Three pointers, spaced approximately 0.06 in. apart, were used for each channel. The marking voltage was normally connected to the central pointer, but the arrival of a positive sound pulse shifted the voltage to a side pointer. Thus the arrival times of sound pulses at the microphones of an array could be recorded, but not necessarily the characteristic wave traces of the pulses.

The time scale was provided by a series of dots along both sides of the record.

A paper drive with spring motor was developed which ran for two minutes on one winding, or which could be operated continuously by winding during the operation.

The Binaural Outpost.[13] The original object of this work was to develop a binaural listening device which could be used as a sound-ranging outpost in the standard gun-ranging method. Such a binaural outpost (Binop) might be used as a substitute for the outpost observer (as shown in Figure 7), or used in addition to him to enable the more highly trained personnel usually located at the sound central to check the work of the observer.

A high-quality Binop covering a frequency range of approximately 50 to 9,000 c was developed for the Field Artillery Observation Battalion outpost work. The Binop consists of the outpost unit and the sound central unit, as shown in Figure 8. The first is a two-channel sound pickup and amplifier mounted inside a case simulating the human head. Associated with it is a stake, on which the head is mounted, and a battery box for power. Binding posts are provided for terminating the wire transmission lines and a standard field telephone circuit. The sound central unit is a small, box-mounted control panel with binding posts for terminating lines from the outpost unit, a field telephone, and a controlling device. Associated with this

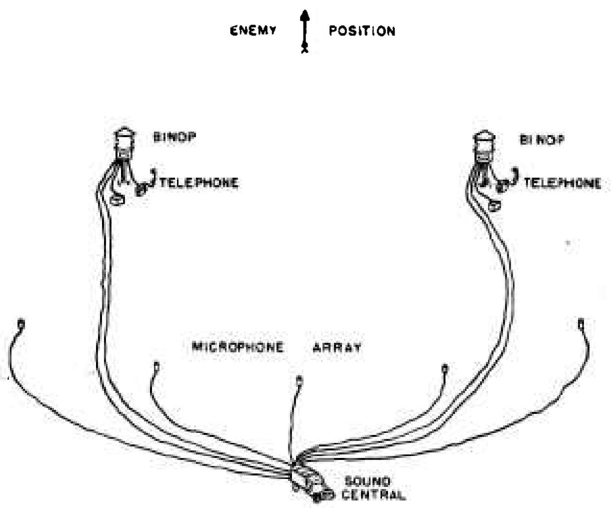


FIGURE 7. Use of binaural outpost in sound-ranging system.

unit is a pair of high-quality head receivers. The Binop weighs approximately 39 lb, divided as follows: head, 23 lb; battery supply, 8 lb; stake, 5 lb; sound central unit, 3 lb.

The channel from each microphone consists

of an input transformer, a three-stage resistance-coupled amplifier with negative feedback around all three stages, and an output transformer connecting the wire transmission line. The line is terminated by an impedance-matching transformer to a head receiver. One channel has means for adjusting the feedback voltage to the screen of the first vacuum tube to control the gain of that channel independently of its input gain control. The other channel has a fixed feedback. The gain of both channels is controlled simultaneously by a dual potentiometer unit in the grid circuit of the first tube. The amplifier output transformer, the wire line, and the receiver impedance-matching transformer are connected to provide a phantom circuit for telephone communication between the two ends of the line and for remote control of the amplifier filament supply relay from a switch at the receivers.

Balancing the gains of the two channels is accomplished by means of a switch connecting the inputs to the two amplifiers. The output voltages of the two amplifiers are connected by a switch in series with a pair of head receivers so that the voltages oppose each other. Under this condition, any sound picked up by the microphones will result in opposing voltages at the amplifier output; if the gains are equal, the resultant voltage across the head receivers will be zero. Therefore, by listening on the head receivers to a sound being picked up by the microphones and adjusting the gain of one amplifier by means of the feedback control until a minimum of sound is heard, the gain of the two amplifiers is equalized. Poling the wire transmission line to maintain the proper phase relationships between the signals in the two channels is accomplished in a similar manner.

This outpost system was completed and tested by the Field Artillery Board. It performed the functions for which it was designed, but the Board decided that these functions were not sufficiently valuable to warrant the transportation of the necessary equipment.

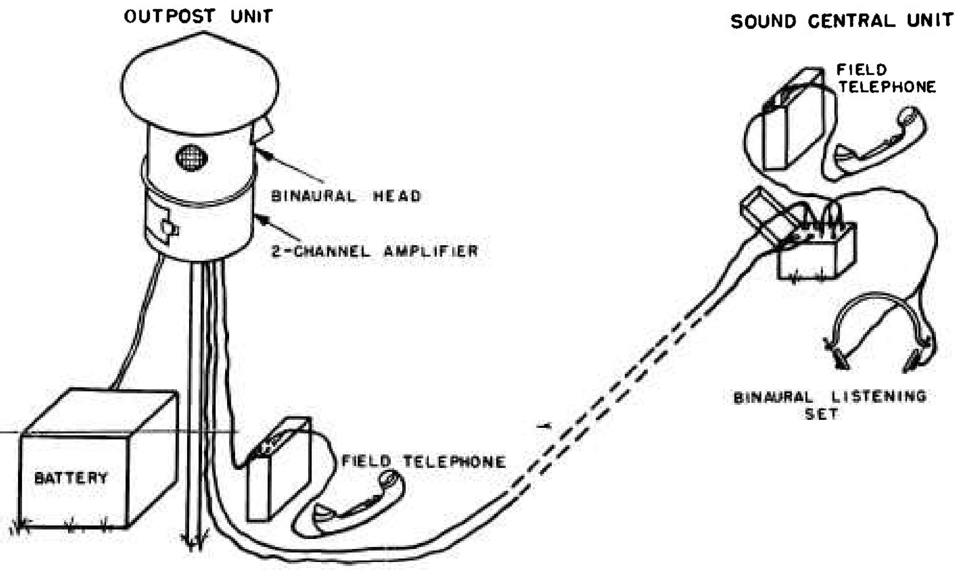


FIGURE 8. Binaural outpost and sound central installation.

5.3.2 Handling the Data

METHODS

Standard Plotting and Methods of Weighting.[2] In the sound plot of the standard method of sound ranging, rays (representing corrected asymptotes) are drawn from the mid-point of each sub-base, and these intersecting rays form the so-called *polygon of errors* or *cat's cradle.* In standard practice the probable location of

the sound source is made either by inspection or by more careful evaluation, but in either case equal weight is given to each intersection. It was the purpose of this work to investigate what method of weighting the intersections would yield the best results. Two cases were considered: (1) all sources of error were lumped together in a time error (taken as 1 millisecond) at each microphone; (2) the error for one microphone was taken as 10 milliseconds, all other errors being neglected.

In the case of a straight base with six microphones and the same error in arrival time for each, analysis of field records revealed that the error in location will be minimized by weighting the following equally: (1) the average of the four intersections of adjacent asymptotes; (2) the average of three intersections of asymptotes separated by one; (3) the average of the two intersections of asymptotes separated by two; (4) the intersection of the two outside asymptotes.

In actual practice the intersections of asymptotes separated by one are preferred, because they are more reliable than the intersections of adjacent asymptotes, or of widely separated ones. Intersections of widely separated asymptotes are less dependable because of nonuniformity of "met" conditions and terrain.

The effect of an error in the arrival time of a sound is greater the greater the distance between source and microphone.

It was found that for a five-microphone base with a 2-sound-second separation, if accurate location to within 150 yd (in range) at 10,000 yd is desired for azimuths between 45 and 90 degrees (the latter referring to the source on the perpendicular bisector of the base), no time error greater than 1 millisecond can be tolerated at *any* microphone. If there is an error of 10 milliseconds at *any* microphone, the maximum range for which a 150-yd accuracy can be secured for the same azimuth range is reduced to about 5,000 yd.

Analytical Method of Computing.[3] One of the functions of the physical research group of the Division was to study the problem of securing simpler and, if possible, more accurate methods of computing sound-ranging data. Consideration was given to ways of minimizing the effect of errors in the time intervals used to determine location of sound sources, regardless of the causes of the errors. The purpose of the project was to eliminate the use of the standard plotting board and to avoid the inaccuracies present in such substitutes as wooden boards with strings. It was generally understood that the Field Artillery Observation Battalions considered the standard plotting board very cumbersome and difficult to move from one place to another. For this reason many battalions replaced this board by a homemade substitute of wood, on which paper scales and strings were mounted. Tests conducted by members of the Division using such boards and sound-ranging records from Fort Bragg showed the inadequacy of the simplified plotting boards.

Two general methods were devised: (1) the analytical asymptote method and (2) the multipolar coordinate method.

In the analytical asymptote method, formulas were developed which give the rectangular coordinates of the points of intersection of the various pairs of asymptotes with respect to one of the microphones as a reference center. These formulas involve the microphone separation, called $2a$, and quantities d_{jk} which are defined as half the products of the effective horizontal velocity of sound by the time intervals between arrival times at the microphones M_k and M_j. The resulting formulas are rather complicated, and tables were prepared to aid in evaluating the terms containing radicals. The formulas remain valid and workable as long as any three microphones of the straight base are in operation. No plotting is involved, so no errors can result from plotting inaccuracies. Because this method uses the intersections of the asymptotes rather than of the hyperbolas themselves, a preliminary determination of the location of the sound source must be made to ascertain the appropriate asymptote corrections to be applied. Even though the use of suitable tables and charts decreases the amount of computation decidedly, a considerable amount of computation is still required—a serious disadvantage. As a result of several trials, it was rather generally agreed that a method requiring less computation would be more desirable for field use.

The multipolar coordinate method has the advantage of avoiding the asymptote correction. Considered as a purely analytical method, it also requires excessive computation. It served, however, as the foundation for the development of a nomographic method which is felt to have considerable possibilities and which has evoked favorable comment in field trials.

For both the analytical asymptote method and the multipolar coordinate method, the individual locations were averaged by a least squares reduction as well as by taking an arithmetical average. The results did not show sufficient improvement to warrant the field use of the former method in preference to the latter.

Nomographic Method of Computing.[3, 4, 11, 20] In the multipolar coordinate method, the distances of the sound source from each inner microphone of a regular straight base may be found from a formula which relates the distances R_1, R_2, etc., to the microphone separation $2a$ and the difference in the times of arrival of the sound at the different microphones $t_{j\text{-}k}$. Introducing the quantities $\lambda_{jk} = V_H t_{j\text{-}k}$, where V_H is the effective horizontal velocity of sound, one obtains by means of certain trigonometrical relations and the fact that distance is the product of velocity and time the formulas

$$R_2 = \frac{(\lambda_{12} - 2a)\ (\lambda_{12} + 2a)}{\lambda_{12} - \lambda_{23}} - \frac{\lambda_{12} + \lambda_{23}}{2} \qquad (1)$$

$$R_1 = R_2 - \lambda_{12},\ R_3 = R_2 + \lambda_{23}, \text{ etc.} \qquad (2)$$

The presence of only linear terms makes the R's easy to compute, and there is no asymptote correction. The position of the source may then be obtained from the points of intersection of the circular arcs of radii R_1, R_2, etc., drawn from each microphone M_1, M_2, etc., as centers. (It is from this that the method takes its name.) To avoid constructing the circular arcs, an analytical alternative was worked out whereby the coordinates of the intersections of each R with every other R may be computed from formulas. These formulas are, however, too complicated for practical field use.

Nomographic version of multipolar coordinate method. The next step in the improvement of the multipolar coordinate method was the development of equations in a form appropriate for constructing a nomogram to be used in determining locations from data obtained by standard sound-ranging methods. Consider three microphones, M_1, M_2, and M_3, equally spaced along a straight line. Let R be the desired range of the sound source relative to the central microphone, and θ the azimuth or angle which the range vector makes with the normal to the base line. Then, from the same principles as were referred to in the preceding paragraph, two basic equations may be derived relating R and θ to the differences in arrival times of the sound at the microphones. These basic equations are

$$A^2 + \frac{4BR}{V_H} - \left(\frac{16a^2}{V_H^2} - B^2\right) = 0 \qquad (3)$$

and

$$\frac{4a \sin\theta}{AV_H} - \frac{BV_H}{2R} = 1 \qquad (4)$$

where $2a$ is the microphone separation, V_H the horizontal effective velocity of sound, and A and B are defined as follows:

$$A = t_{1\text{-}2} + t_{2\text{-}3},\ B = -t_{1\text{-}2} + t_{2\text{-}3} \qquad (5)$$

A and B are determined from the time differences; then, for a given A and B, R may be found from equation (3); and finally, with R known, θ may be found from equation (4). It was believed that these steps of computing R and θ from equations (3) and (4) could be done most easily by means of a nomogram. Two forms of the resulting nomogram are shown schematically in Figures 9 and 10. Along the left edge of each is an A scale for which distances from the base are proportional to A^2, and along the right edge is a range scale which is linear in R. The sloping B curve in each is constructed in accordance with a rather elaborate formula. Two identical linear A scales are shown at the top and bottom in Figure 9, and one such scale near the bottom of Figure 10. At the bottom of the latter is an azimuth scale, whose distances are proportional to $\sin\theta$, with additional B scales on each side. Throughout the major portion of Figure 9 are constant-azimuth curves. These are obtained by eliminating R between equations (3) and (4) and then, for a chosen θ, finding values of B for different values of A, each pair of A and B values giving one point on the given constant-azimuth

curve. To use the nomogram of Figure 9, the predetermined value of A on the left edge is connected with the predetermined value of B on the B curve. The extension of this line EE to the range scale gives the range. With the same value of A, corresponding points on the

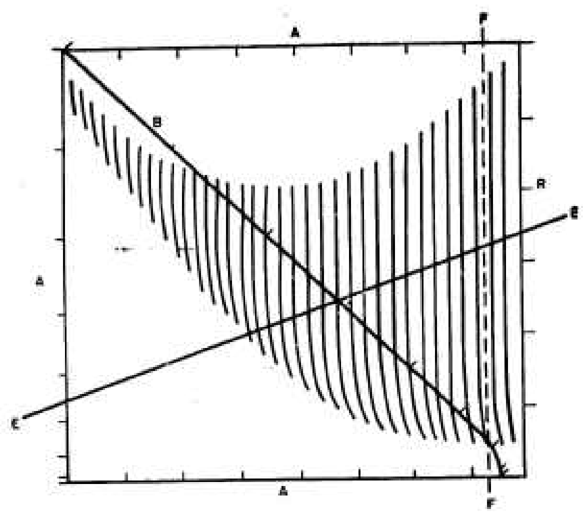


FIGURE 9. Nomogram schematic—nomogram with constant-azimuth curves.

upper and lower A scales are connected. By reading the value in the field of constant-angle curves of the intersection of this line FF and the one previously drawn, the azimuth is found. An alternative method of obtaining the azimuth is to make use of the θ scale at the bottom of the nomogram of Figure 10 in conjunction with the associated A and B scales. This method is expected to be used in only the relatively few cases—chiefly when the sound source is well on the flank at short range—for which the first method is inadequate. In this alternative method, the range is determined as before; then this value of R is connected to the value of A on the bottom A scale. The intersection of this second line KK, extended, with a horizontal line through the correct value of B on the vertical B scale gives a point whose projection on the azimuth scale is the corresponding value of θ.

Case of one microphone inoperative. Nomograms were also computed for the case where the separation between the second and third of a group of three microphones is twice that between the first and second, and for the case where the separation between the first and second microphone is twice that between the second and third. Such situations arise when one of the inner microphones of a four- to six-microphone base becomes inoperative. In this case two nomograms are necessary, in addition to the standard one for the completely operative base, to take care of all possible cases which may arise.

Results of plotting by the nomographic method. For a five- or six-microphone base, R and θ values may be found for each group of three microphones. If azimuth lines and range points are located on the plotting grid, the location of the sound source may be taken as the point halfway between the average of the range points and the average of the intersections of the azimuth lines. However, in view of the results of some tests conducted by the Field Artillery Board, Fort Bragg, North Carolina, it appears that more weight should be given to the intersections of the azimuth

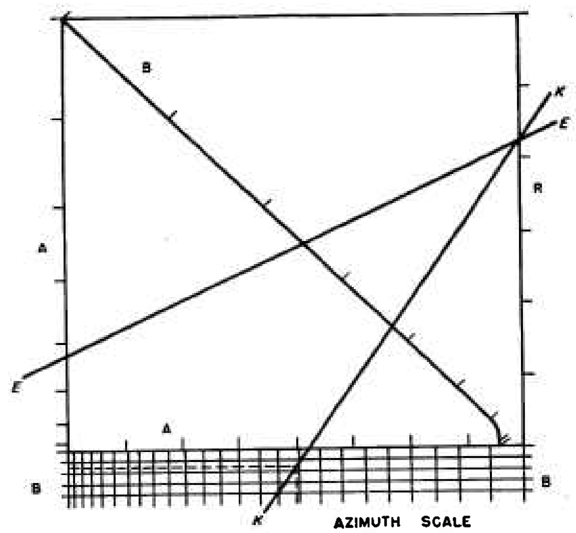


FIGURE 10. Nomogram schematic—nomogram with lower B scale.

lines than to the range points, the former being much less affected by slight errors in reading the film, etc., than the latter. A comparison of the accuracy of location determined by using the standard method, the analytical asymptote

method, and the nomographic method showed that, so far as field operations are concerned, the nomographic method is the best.

Ballistic-Burst Method.[12] The purpose of this work was the development of a new method of sound ranging which would utilize the arrival times of the ballistic wave and the shell-burst wave at the microphones of a sound base of the type used in the standard sound-ranging method. The development was started on August 16, 1943, at the suggestion of the Field Artillery Board. It was pointed out at that time that reports from Observation Battalions operating in Tunisia indicated that sound records were frequently obtained on which the gun wave was inaudible and only the ballistic wave and shell-burst wave arrivals were recorded. In view of this fact, the Field Artillery Board was of the opinion that an investigation should be initiated to determine the possibility of obtaining information regarding gun locating using only the ballistic wave and shell-burst wave data. It was felt that even a determination of the azimuth of the gun position would materially reduce the area which would have to be searched. A rough determination of the range would still further reduce the aerial search problem, even though the approximate sound location taken alone might not be sufficiently accurate for direction of counter-battery fire.

Conditions for the use of the method. When the "met" measurements indicate that a negative gradient of sound velocity with height exists in the direction from the gun to the base line, the conditions are rather unfavorable for sound ranging by the standard method on sources at large distances from the base. Even though the conditions are extremely unfavorable for the transmission at long range of a gun wave originating at ground level, it is still very probable that the ballistic wave and shell-burst wave will be audible at the base, since the ballistic wave is generated by the shell at a point considerably closer to the base line and some distance above the surface of the ground, whereas the shell-burst wave will ordinarily originate from a point much closer to the base than the gun position. Frequently, the shell burst occurs behind the microphone base, so that the sound-velocity gradient is favorable for transmission back to the base. However, it should be emphasized that this method is not to be considered a replacement for the standard method of sound ranging but rather an extension of it, to be used in those cases in which the standard method does not give satisfactory results.

Line-of-flight determination. The determination of the line of flight of a shell is based on the fact that the trace of the ballistic wave on the ground is symmetrical with respect to the line of flight. The steps are as follows:

1. It is first necessary to construct the trace of the ballistic wave on the ground. This trace is constructed by selecting the earliest arrival time as a zero reference and measuring the time intervals between this reference and the arrival times at all the other microphones. These time intervals are corrected to standard temperature of 50 F and converted into distances. These values represent the distances from the various microphones to the ballistic wave front at the time the wave front was incident on the microphone at first arrival.[b]

2. If circles are drawn around the various microphones with radii equal to the corresponding distances obtained above from the time intervals, then the instantaneous position of the trace of the ballistic wave on the ground is a curve tangent to all these circles and passing through the zero reference microphone (see Figure 11).

3. Next, the shell-burst position is found by means of the shell-burst wave arrival times, using the standard method of sound ranging.

4. After the shell-burst position is located, the line of flight is found by striking an arc with center at the shell-burst location and radius such that the arc intersects the ballistic ground-trace curve in two points, separated by a distance equivalent to about 2,000 yd at the scale of the map.

5. With these two points as centers, two intersecting arcs of equal radii are drawn. The intersection of these two arcs determines a

[b] A certain degree of approximation is assumed here since the ballistic wave does not approach the microphones horizontally and wind effects are neglected. However, investigation showed that the above method is sufficiently accurate for sound ranging.

second point on the line of symmetry. Thus the line connecting the shell-burst position and this second point is the line of flight of the shell (see Figure 11).

6. It should be noted that this method can be used only if the line of flight crosses the base line; however, it is possible to treat the case in which the line of flight passes within one sub-base length of the end of the base.

Range determination. After the method of determining the line of flight had been completed, an investigation was started to determine the feasibility of obtaining a value of the range.

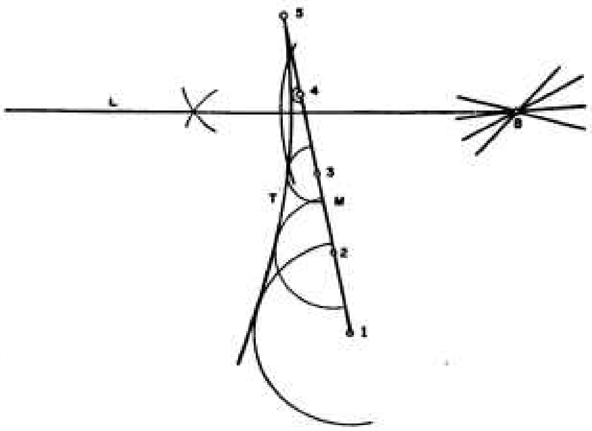


FIGURE 11. Line-of-flight determination.

The time interval between the arrival of the ballistic wave and the shell-burst wave at the point of intersection of the line of flight and microphone base line can be calculated. It is possible, though not very likely, that two guns with different muzzle velocities and total ranges might give the same time interval; another pair of different guns might give identical ground traces of the ballistic wave through a given point. Thus, neither the time interval alone nor the shape of the ground trace alone completely specifies the gun type, muzzle velocity, and range. However, it is very improbable that two different guns which give similar ground traces would also have equal time intervals between the arrivals of the ballistic and shell-burst waves, or vice versa. Thus it would seem that a consideration of both the shape of the ground trace and the time interval would be sufficient to determine uniquely the type of gun, muzzle velocity, and total range. This was the case for the German guns.

To summarize, the following data available to the sound-ranging unit are in excess of those required for determining the line of flight: (1) distance d from shell burst to the ground trace of the ballistic wave; (2) time interval between arrival of the ballistic wave and shell-burst wave ($\Delta\, t_{SB}$); (3) curvature of the ballistic wave ground trace. Corresponding to these three observable quantities are the following unknowns: (1) type of gun, (2) muzzle velocity (charge), and (3) total range. Though it should be possible to solve for the three unknowns in terms of the observable quantities, it was found that the mathematical relationships between the observables and the unknowns were too complicated to be put in a simple form for field use. It was therefore necessary to resort to a graphical solution of the problem.

This solution took the form of a series of templates giving the shape of the ballistic wave ground trace, for various ranges, for a particular type of gun, charge, and distance d from shell burst to ballistic wave ground trace. (For a sample template see Figure 12.) For each gun and charge, templates were constructed for particular values of d to cover the region within which shell bursts might normally be expected.

In addition to these templates, a set of tables were made up, giving the time interval between the arrival times of the ballistic and shell-burst waves as observed at the intersection of the base line and the line of flight. These time intervals were tabulated for various guns, charges, and ranges for particular values of the distance d.[12]

If the type of gun is known from other intelligence reports, the solution for the range to the gun is found by using the template appropriate to that type of gun and the range curve on that template which fits the plotted ballistic wave ground trace.

If the type of gun and muzzle velocity are not known, it is necessary to repeat the procedure, using templates for each of the possible combinations of gun type and muzzle velocity for

which data are available. The resulting list of range values corresponding to these cases could be quite formidable, but the number can usually be considerably reduced by experience and the aid of intelligence reports.

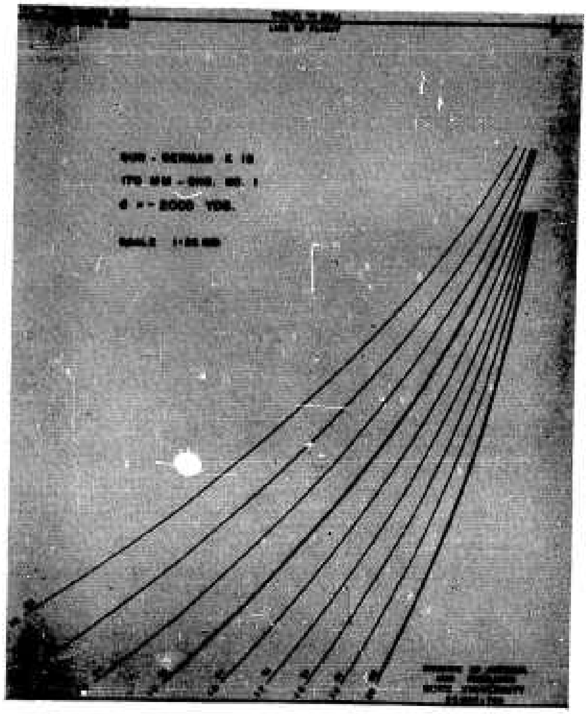


FIGURE 12. Sample template for giving shape of the ballistic wave ground trace.

When the list of possibilities has been narrowed down as much as possible, the ballistic-burst time interval tables are used to determine the theoretical time intervals for the various combinations of gun, charge, and range which have not been eliminated. A comparison of these values with the experimental time interval should reveal a single combination of gun, charge, and range.

The use of the ballistic-burst time interval involves more approximation than exists in the use of the templates. This accounts for the use of the templates for the range determination, whereas the time interval is used as a qualitative check to determine the type of gun and charge and not for a quantitative determination of the range.

A method of applying ballistic and meteorological corrections to this method of sound location was developed which corrects for the effects of meteorology and drift on the trajectory, and for the effects of meteorology on the sound transmission of the shell-burst wave. However, it is not possible to make any correction for variations in muzzle velocity due to wear of the gun, since this data is not available under battle conditions. This results in an uncorrectable error in range—the limit of the accuracy of the method.

Extensive field tests were carried out at Fort Bragg, North Carolina, which proved the greater efficiency of this method over the standard method under favorable "met" conditions. The tests further showed that the method served the purpose for which it was developed. The error in line or azimuth was estimated to be about ± 10 mils (6,400 mils = 360 degrees), as seen from the shell-burst position, for an azimuth of not more than 30 degrees. Thus one dimension of the rectangle of error is 1 per cent of the observed range. The error in range is mainly determined by the unknown wear of the enemy gun. In the absence of any information from other sources on the wear of the gun, this error was estimated at about ± 500 yd for ranges of 20,000 yd or greater. The residual experimental error of the method was about ± 100 yd. Thus this method is comparable in accuracy with the standard method for ranges over 20,000 yd; for short ranges, however, it is less accurate, and should be used only as a rough check when results of the standard method seem doubtful.

Study of "Met" Corrections.[2, 10] The errors in sound ranging fall into two classes: instrumental errors and propagation errors. The propagation errors include the effects of meteorology and terrain on sound waves. Thus in the standard method of gun ranging a meteorological correction must be applied to each measured difference in arrival times. The techniques of and equipment for acoustic gun ranging are sufficiently advanced so that the instrumental errors are smaller than or, at most, of the same order of magnitude as the propagation errors. Therefore, a study of the best method of applying a meteorological correction to data obtained by the standard method

was considered important and was undertaken by the Division.

Various methods were compared; the following were regarded as important enough for special study: (1) the standard correction now in use by the U. S. Field Artillery for a straight base; (2) the Goodwin method developed in Great Britain for use with a straight base; (3) the U. S. Army Signal Corps triangular array method;[30] (4) the V_H method developed by the Second Field Artillery Observation Battalion.

The standard meteorological correction method is described in Field Artillery Field Manual FM 6-120 and has been outlined briefly in Section 5.2.1 of this report. It is used with a straight base and the GR-3-C recording system and (in a modified form) with the Dodar system (see Section 5.4). The method was critically studied by members of the Division; in general, application of meteorological corrections by this method was found to improve the results statistically, but the effectiveness varied considerably in individual cases, and in some cases was very inadequate. Two serious objections are pointed out: (1) in determining the effective wind speed and direction, the wind velocities at the various heights should be weighted as vector quantities; (2) the determination of the effective temperature is too arbitrary. A reconsideration of the weighting factors based, if possible, on theoretical considerations, is recommended.

The Goodwin method[31] is more elaborate, being essentially a numerical calculation in the calculus of variations. It also requires the preparation and use of a set of tables. However, its formulas are based entirely on theoretical considerations, assuming again a steady and horizontally stratified atmosphere. Two objections to this method are its complexity and the fact that only the wind component parallel to the plane of propagation is considered, crosswinds being neglected.

The Signal Corps method is applicable to the triangular base. As in the Goodwin method, rather elaborate calculations are called for; this method is also based on theoretical considerations and the assumption of a steady and horizontally stratified atmosphere. A fundamental element in this method of correction is the so-called *criterion curve* which is a plot of $V(z) + w(z)$ versus z, where $V(z)$ and $w(z)$ are, respectively, the scalar velocity of sound and the wind component in the plane of the sound ray at the height z above the ground. This curve is obtained from a vertical sounding of the atmosphere. An immediate advantage of obtaining the criterion curve is that one may determine whether or not there are multiple paths. The sound path may be plotted in each case. The atmosphere is divided into horizontal layers, and the horizontal distance traveled and drift determined for each layer. Thus allowance is made for cross-winds. The Signal Corps method is also independent of the possible existence of multiple reflections at the ground in the transmission from source to microphone base, whereas the other methods are not.

The V_H method is essentially an attempt to apply some of the features of the Signal Corps method (notably the criterion curve) to the standard straight or curved base. This necessitates placing two auxiliary microphones behind the standard base to give the equivalent of a straight base and two triangular bases. The auxiliary microphones make it possible to compute the effective horizontal velocity of sound at each end of the standard base. Intermediate values are computed by interpolation. The arrival times at each microphone can then be corrected to what they would be for standard conditions (no wind and a temperature of 50 F). Furthermore corrections for drift due to cross-winds may be computed, if desired, as in the Signal Corps method.

A comparative test of the four methods outlined above was made using a rather small amount of data obtained during actual artillery fire for which the true location of the source was known in each case. The more elaborate methods proved to be little, if at all, superior to the standard Field Artillery method. These results are in agreement with those of a somewhat similar comparison made by the British.[32] It is possible that the Signal Corps or the V_H method may be superior for long-range locations in which overhead paths may be important. From the theoretical point of view,

these two methods would seem to be preferable; but on the practical side, one must consider such factors as ease of computation, availability of sufficient and accurate meteorological data, the actual meteorological structure, and the type of base which is easiest to set up and maintain.

EQUIPMENT

Trace-Reading Templates. One of the sources of error involved in the transfer of data from the sound-ranging record to the final plot lies in the determination of the exact time of the initial break on the record. The nature of this break varies over wide ranges with respect to the sharpness of the initial inflection. When breaks are sharp, an experienced film reader can usually determine them to within 0.002 second. Under usual sound-ranging conditions, this degree of accuracy results in only minor errors in the plot. Very often, however, the time breaks are quite rounded, and even experienced film readers may vary as much as 0.010 second in their estimates. Errors of this magnitude can result in range errors up to 150 yd and more for ranges of 10,000 yd and over. Inexperienced film readers, who may necessarily be utilized under battle conditions, can increase this error considerably. In an attempt to reduce the error resulting from visual film reading, several types of reading scales were devised and tried in the field.

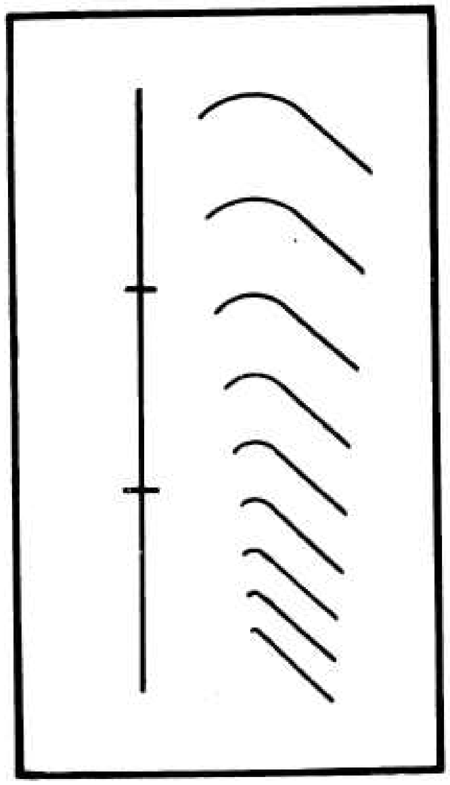


FIGURE 13. Trace-reading template.

The reading scale devised to assist in the accurate determination of the initial breaks consists of a series of varying-sized quadrants of circles with tangents extended from one end, as shown in Figure 13. In use the proper "hook" is determined by matching the curvature of the hook to the particular gun break. The scale is then rotated so that the tail lies tangent to the steepest part of the wave. The time of first arrival is then read at the dot or center of the quadrant. The reading scale is adaptable to any amplitude of break since variations in amplitude merely rotate the hook about its center or dot.

In addition to the series of hooks, a straight line having crosslines is included on the reading scale. This may be used to determine the point of first crossover of the gun wave conveniently and accurately.

Field tests of the reading scale proved that a substantial improvement in accuracy and especially uniformity results from its use. On a series of gun waves with varying degrees of curvature, three film readers, estimating without the aid of the reading scale, varied in their estimates of the sharpest breaks by 0.002 second, and of the most rounded breaks by 0.008 second. The same three readers, using the reading scale, located the same breaks with a variation of only 0.001 second for the sharp breaks, and 0.002 second for the most rounded. This indicates much greater consistency in reading by different observers.

Over 800 copies of this template, printed on Lucite, were manufactured and furnished the Field Artillery Board. Some of these copies were flown to the fighting fronts.

Nomogram and Accessories—The Plotting Grid.[11, 15, 20] The theory of the nomogram, with

schematic diagrams illustrating its method of use, has been explained in Section 5.3.2. Nomograms were computed and master drawings were made for the following: 2-sound-second straight base, 4-sound-second straight base, and 4-sound-second straight base with inoperative inner microphone (two nomograms required to take care of all possible situations). These nomograms may be used for any uniform microphone separation on a straight base by use of suitable multiplying factors. An investigation was next made of the best method of making prints of the above nomograms and of the best type of base and reading mechanism on which to mount such prints. The development of an improved method of plotting necessitated the design of auxiliary plotting equipment. Finally a suitable case for carrying all the above equipment was designed and built.

In the development work just outlined the following military requirements had to be kept in mind: (1) the equipment must be light and portable; (2) the equipment must be rugged and corrosion-proof; (3) sliders must move easily and be self-locking when released; (4) scale settings must be accurate, with special means to avoid parallax.

All these requirements were met in the final models supplied to the Field Artillery Board for field tests; at the close of the contract, however, design for quantity manufacturing had not been started.

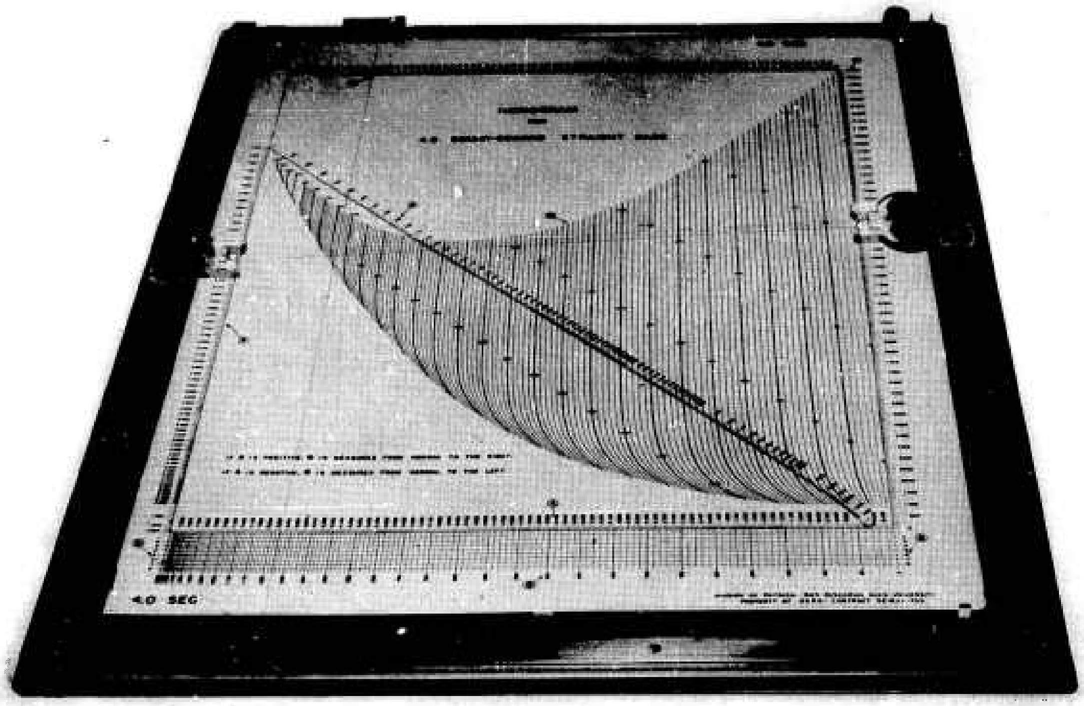


FIGURE 14. Final nomogram mechanism with mounted nomogram chart.

Nomographic equipment included the following:

1. Four nomogram charts. These charts, about 20 by 16 inches, were printed on Lucite by the Sweeney Lithograph Company, Belleville, New Jersey, using a special ink developed by this company for the purpose. The charts are coated with "Sweeney Hardcoat" for protection. On the back of each chart is printed a grid on a scale of 1 to 25,000 (in yards). This coating

could be made suitable for marking and erasing, and it proved to wear well.

2. A nomogram base and reading mechanism (shown in Figure 14 with one of the charts mounted on it). The base is made of stainless steel. The sliders on the sides are connected by two extendible nylon filaments, one above the other so as to eliminate parallax. The top and bottom sliders move together, through an arrangement of cables and pulleys, so as to keep the filament stretched between them always at right angles to the top and bottom *A* scales.

3. A portable microphone base to be used with plastic plotting grids. This base is made of Lucite and can be attached to the plotting board by means of vacuum cups.

4. A device for drawing normals to the base line, also of Lucite.

5. A protractor or fan, similar to the standard plotting fan, but made of Lucite.

6. A carrying case. This can be used as a plotting table. The case measures 29½ by 23¾ by 3¾ in. and, together with the above equipment, weighs 33 lb. Future plans contemplated an all-welded case with gaskets and weather-protecting paint.

Advantages of the nomogram:

1. The nomographic equipment is much lighter than the standard M-1 sound-ranging board.

2. The preliminary plot for curvature correction required in the standard method is eliminated.

3. The range determinations, being much more sensitive to fluctuations in atmospheric sound transmission than are the azimuth determinations, afford a means of judging the type of weather, terrain, etc.

4. The accurate methods of plotting developed in connection with the nomogram proved sufficiently superior to standard methods so that a request was made to extend the development of plotting methods to include all Field Artillery plotting (see the next section).

5. Extensive field tests showed that the nomogram will yield results of a high degree of accuracy, provided gross human errors are eliminated. (In the tests at Fort Bragg, such errors played a considerable role, causing the nomogram to make a poorer showing than did the standard methods.)

Artillery Plotting Grids.[15] In standard plotting practice, points are marked on translucent paper which has been superimposed on a cross-section paper map. All forms of paper used for these grids and for plotting the location of enemy targets are subject to changes in size and shape as a result of changes in humidity and temperature. This inherent warping results in errors of location of as much as ±50 yd at a range of 20,000 yd. The development of Lucite grids for use with the nomogram and the necessity for extreme accuracy led to the development of such grids for all artillery plotting. These grids consist of rectangular sheets of Lucite ruled on one face with squares whose sides represent 1,000 yd, usually on a scale of 1 to 25,000. The other side is similarly ruled in 100-meter squares. The grids were

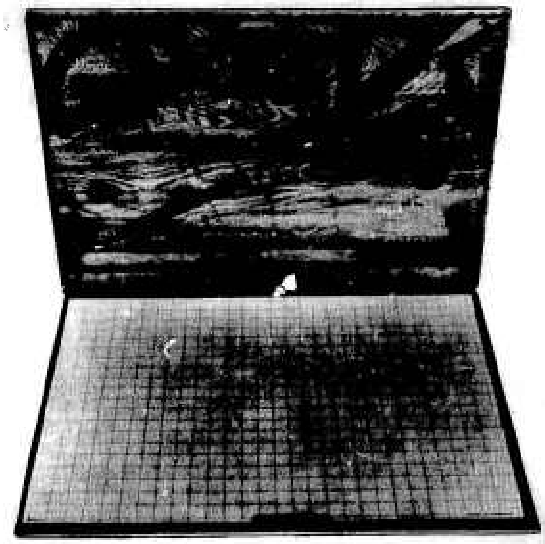


FIGURE 15. Carrying case with grids and accessory plotting equipment.

housed in a suitable carrying case (see Figure 15).

The results of laboratory tests and field tests at Fort Bragg showed that the Lucite grids ensure greater accuracy than any plotting means yet developed. These grids, together with Lucite plotting fans and Lucite locators mounted on vacuum cups, have been found

to reduce the errors in location due to warping, etc., to an average of ±10 yd, thus reducing the cost of neutralizing an enemy target by a factor of from 1 to 25.

The Lucite grids and accessory equipment provide an important time saver, with the desired flexibility necessary for the quick firing encountered in mobile warfare.

They may be used for plotting target locations on their surfaces. Location marks can be readily removed by erasing, without injury to the surface.

Field tests indicated that contact with grit, dirt, leaves, and even rain does not impair the usefulness of the grids.

burst to the ground trace of the ballistic wave, the problem was to determine the ballistic wave ground trace for each of a series of ranges of the gun. Since no sufficiently accurate equation for the coordinates of an actual trajectory is in existence, it was necessary to resort to a graphical method of solution.

A series of trajectories was constructed, spaced at 1,000-yd intervals in total range throughout the range values to be considered. Each of these trajectories was specified by the coordinates of points at 1-second intervals in shell travel time up to the point at which the shell velocity dropped below the velocity of sound. A sample chart of this type is shown in

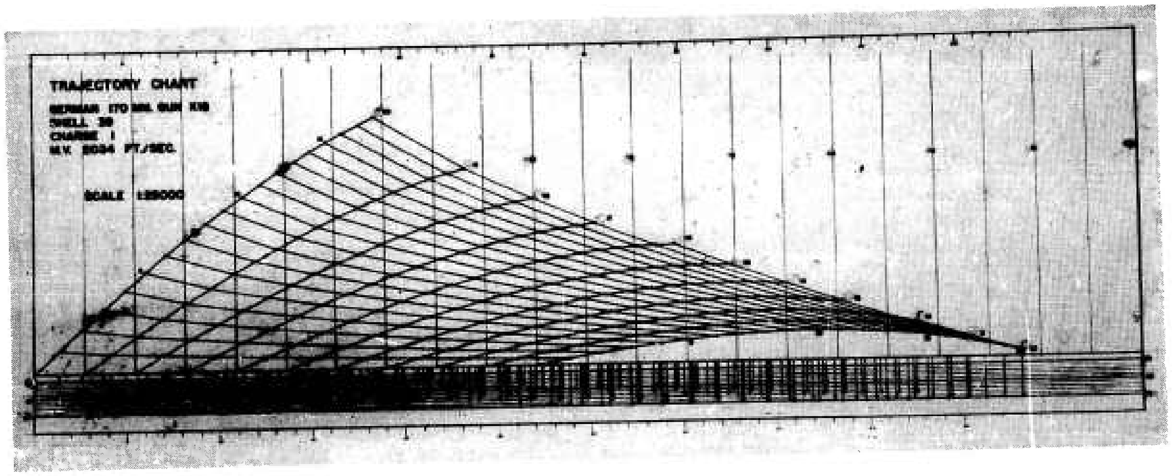


FIGURE 16. Sample trajectory chart.

Ballistic-Burst Templates and Tables.[12] In the description of the ballistic-burst method the need for templates and tables prepared for each gun in question was explained. Construction of these templates and tables was possible only by a graphical method involving much laborious work. For each gun the following data had to be compiled: (1) the coordinates of the time points for the trajectories of the gun (provided by the Aberdeen Proving Ground), and (2) the firing tables for the gun (furnished by the Field Artillery Board).

Templates and tables were prepared for the German 170-mm K18, the German 210-mm Mrs 18, and the American 155-mm M-1. In constructing a template for a given gun, charge, and fixed value of the distance d from shell

Figure 16. In plotting the trajectories it was convenient to make the shell-burst position common for all trajectories, since this is the common reference point for any given template. The adjacent points on a given trajectory were connected by straight-line segments for convenience in following a given trajectory, and the range in 1,000-yd units was marked at several points. These connecting lines were for guidance only. In a similar manner the points of equal time on adjacent trajectories were also connected by straight-line segments, and the time value in seconds marked at several points. This double family of curves formed a convenient coordinate system for locating a particular time point on any given trajectory.

The construction of the templates required

the projections of all the trajectory points on the horizontal or x axis. When a large number of trajectories were plotted on the same chart (Figure 16), the array of vertical lines became very difficult to follow; therefore, the following method was adopted. A series of equally spaced lines was drawn parallel to the horizontal axis and just below it. Each one of these lines was numbered to correspond to one of the trajectories plotted on the chart, every fifth line being made heavier. The projections of the points of a given trajectory were then marked on the corresponding horizontal line, and a short vertical line drawn back from these projection points to the x axis to determine the actual projection point on this axis (bottom of Figure 16). The advantage of this system is that the projection of a given time point for any particular trajectory can be selected by eye from the horizontal line corresponding to this trajectory. When this point has been found, it is necessary merely to follow the short vertical line from this point to the x axis, a distance never exceeding 2 in. Experience showed that this method of projection materially increases the speed of the construction process.

On the sheet which was to be used for the master template (see Figure 12) a line was drawn parallel to the upper edge and about half an inch from this edge. This line represented the line of flight with reference to which the template curves were to be constructed. About half an inch from the right edge of the template sheet a short vertical line was drawn across the line of flight. The intersection O of this line and the line of flight was taken as the reference point or vertex of all the curves on the template. The template sheet was placed on the trajectory chart in such a manner that the line of flight coincided with the x axis of the trajectory chart; the short vertical line was set at the particular distance d from the shell burst for which this template was to be constructed. (This sheet was located so that the main construction area extended below the x axis and would not cover any of the trajectory points.)

The ballistic wave ground traces passing through the reference point O on the suitably located template sheet were constructed by locating first the apparent ballistic origin for this point on a given trajectory. This apparent ballistic origin was that point on the trajectory at which the component of the shell velocity in the direction of the reference point was exactly equal to the velocity of sound.

By means of a compass with center at the apparent source for the reference point O, an arc was struck with radius such that it passed through the point O. The center was then moved back one second on the trajectory, the radius increased by one sound-second, and another arc drawn, intersecting the x axis at a point slightly closer to the gun than O. This process was repeated for each of the trajectory points preceding the apparent source for O, always keeping the sum of the shell travel time to a given trajectory point and the radius of the arc from this point in sound-seconds constant. In this way a series of arcs was obtained, intersecting the x axis in the vicinity of the point O. The arcs represented parts of the vertical section of the elementary spherical waves originating on the trajectory. These spherical waves could be considered as intersecting the ground plane in circles. The radius of each such circle would be the distance along the x axis between the intersection of the corresponding arc and the projection of its corresponding trajectory point on the x axis.

In order to keep the construction in one plane, the part of the figure below the x axis was taken to represent the ground plane, and the part above the x axis was taken as the vertical plane of the trajectory. In this way the circles of intersection of the elementary spherical waves with the ground surface could be drawn below the x axis. This was done for all the trajectory points between the gun position and the apparent source for the point O. Inside the region of audibility an envelope curve could be drawn tangent to all these circles. This curve represented the instantaneous position for a given trajectory of the ballistic wave ground trace at the time its vertex reached the point O. This process was repeated for the trajectories of other ranges. A resulting template is shown in Figure 12.

The templates were made by compositing a printed template in a transparent plastic to

facilitate the fitting of the templates to an experimental curve. The method of doing this was developed by the Sweeney Lithograph Company, Belleville, New Jersey, and the E. I. duPont de Nemours Company, Arlington, New Jersey, in cooperation with Duke University. In the finished template the printing is completely protected from the effects of wear.

The tables prepared consisted of (1) ballistic-burst time interval tables and (2) condensed range tables. The former have already been referred to. The time interval between the arrival of the ballistic wave and the shell-burst wave at the reference point was readily calculated from the data obtained in the construction of the ballistic wave ground trace. The values of the time intervals were tabulated as a function of range for 1,000-yd changes in ranges, for a particular value of d, and for all the various guns and charges considered. The condensed range tables were prepared to facilitate the calculation of the range and deflection effects for the shell trajectory when conditions are not standard.

One hundred sets of templates and tables applying to the two German guns (K18 and Mrs 18) were delivered to the Field Artillery Board for shipment overseas. In addition, templates and tables applying to the American 155-mm M-1 gun were delivered to the Field Artillery Board for training purposes.

5.4 NEW METHODS AND EQUIPMENT IN SOUND RANGING

5.4.1 Obtaining the Data

METHODS

Coincident with the work described in the last chapter on possible methods of improving the standard method of acoustic gun ranging, the Division of Physical War Research at Duke University gave its attention to the possibility of developing new methods which might possess certain advantages over the standard method. In this connection an investigation was made of the possibility of (1) ranging by means of seismic waves, (2) developing a sound-ranging method based on the doppler effect, and (3) developing a multiple-short-base method of sound ranging. The first two methods proved unpromising, and work on them was abandoned, but the third method was successfully developed and led to the Dodar system, now adopted by both the U. S. Army and Marine Corps.

Seismic Method.[7] The study of seismic propagation was undertaken to determine the possibility of detecting and ranging artillery by means of earth-borne vibrations. Previous work by others[33] had been limited to investigations of comparatively deep-traveling refracted and reflected seismic waves and had indicated the impracticability of using these waves successfully for gun ranging. Therefore, the scope of this study was limited to the use of waves traveling along the surface of the earth.

The method of utilizing earth-borne vibrations for artillery ranging is fundamentally the same as that of using airborne sound, differing only in the method of detecting the vibrations and in the corrections to be applied. Since the medium in this case is stationary, the only variable which is considered is the change of the velocity as a result of varying earth structure between the source and the detection devices.

As a result of field tests at Fort Bragg the following conclusions were reached:

1. The use of earth-borne surface waves alone for seismic artillery ranging is not feasible because: the artillery-initiated surface waves do not possess sufficient energy at the usual ranging distances to be detected, and the propagation velocity of seismic surface waves varies with the terrain over which the ranging is to be done—a factor extremely difficult to evaluate.

2. While seismic vibrations in the surface layer are initiated by gunfire, these vibrations do not reach the geophones through the ground at distances normally used in sound ranging. They appear to result from and to be of a magnitude proportional to the intensity of the airborne sound, and they arrive almost simultaneously with the airborne sound.

3. The use of geophones actuated by airborne waves is less satisfactory than the use of microphones designed specifically for airborne sound.

Doppler-Effect Method.[22] It was suggested that the doppler effect be employed to determine the direction of arrival of a sound from a gun. This method was analyzed to determine the character of the devices which would be used to apply it.

The doppler effect is most often observed as a change in frequency from that emitted at the source when there is relative motion between the source and the observer. However, such relative motion may be said to cause a change in wavelength of any observed acoustic phenomenon, such as the sound impulse emitted by a gun when it is fired. Such a change is also a doppler effect. In sound ranging on guns the only relative motion which can occur must necessarily be on the part of the observer.

When a gun is fired or a shell explodes at the end of its trajectory, the resulting acoustic wave is highly complex as to frequency. Any attempt to extract from it a single frequency component for the purpose of applying a doppler effect in such manner as to indicate the direction of the wave's origin appears highly impracticable. Because of the impulse nature of the wave, it would seem that the analysis must necessarily be applied to the length, on a time base, of some selected and easily identified portion of the impulse. Since there can be no predetermined and exactly known length for this function, a comparison of two observations of the same impulse would be required. Either one or both of these observations should be modified by the doppler effect. The short duration of the sound would probably require some form of recording device, such as a multiplicity of identical microphones occupying a succession of positions in the sound field in some predetermined and systematic manner. A short base for these microphones is indicated by the requirements for their coordinated movement or switching and by the necessity that the signal received by every microphone should be identical except for the modifying effect of the doppler principle.

No actual device was constructed, but several methods were suggested, such as: (1) two microphones on opposite ends of a rotating boom, (2) a number of microphones uniformly spaced around the circumference of a rotating wheel, (3) microphones attached to a moving belt, (4) microphones moving with linear simple harmonic motion, and (5) stationary microphones with a commutation device for switching each one in and out at such a rate that it would appear as if a single microphone were moving with simple harmonic motion.

Because of the highly transient nature of the sound from a shell burst, it does not appear that there is any practicable means of detecting and analyzing a particular frequency component of the transient after this component has been modified by the introduction of a variable doppler effect. The doppler method, therefore, reduces to the measurement of the changes in the times of occurrence of certain significant and easily identified phenomena in records of the wave motion. Since the measurement of time rather than frequency appears to be the only solution which the method permits, there seems to be no reason to regard the doppler method as possessing significant advantages over the conventional method.

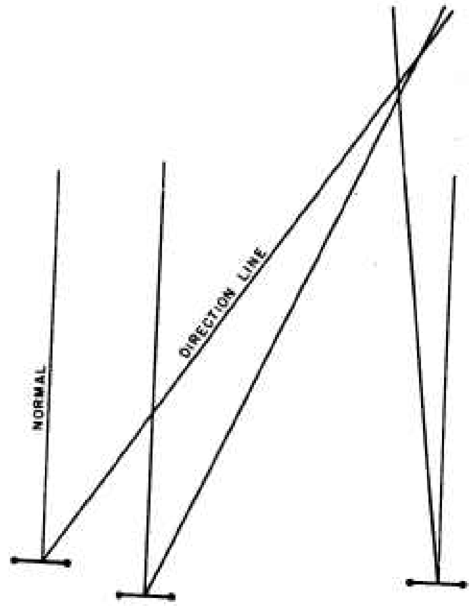


FIGURE 17. Determination of sound source by multiple-short-base method.

The application of the doppler method requires the use of very-short-base microphone arrays, without in any way overcoming the

inaccuracies and deviations which are known to affect the results from such arrays.

There appears to be no obvious method for eliminating from the observations the air disturbances produced if moving, rather than commutated, stationary microphones are used. There is no significant difference between conventional short-base sound-ranging methods and the use of commutated stationary microphones.

Multiple-Short-Base Method.[8, 9] In view of the increased emphasis on mobility and speed of operation, an investigation was made of the possibility of developing a sound-ranging method in which several short bases of two microphones each are employed rather than the standard long straight base of four to six microphones with 2- or 4-sound-second spacings.

If two microphones are located on a line of predetermined length, it is possible by time measurements to determine the position of the sound source, as explained in Section 5.2. Although only two pairs of microphones are required to determine the location of the sound source, three pairs are preferable, as the intersections of the three direction lines seldom meet in a single point, but generally form a triangle, as shown in Figure 17. From this triangle the probable location may be estimated and some idea gained of the relative inaccuracies introduced through variation of "met" conditions and terrain.

Early in 1943 the physical research group of the Division of Physical War Research undertook a series of tests to determine the variations in the propagation of sound due to atmospheric conditions.[5, 10] These tests are discussed in Section 5.5. In general, it was found that the observed time variations were independent of the frequency of the sound, and that the mean time deviation increases with microphone separation in a fairly linear relationship for small separations, with a leveling-off tendency for larger ones. Certain of the data were used in evaluating the requirements to be imposed on the time interval measuring equipment to be used with a short base, and a probability study was made showing the degree to which errors in location are dependent on time variations. The data were of a very preliminary nature and could not be used in setting hard and fast requirements. However, it was found that an instrument having an accuracy of 1 or 2 milliseconds would be satisfactory for use in sound ranging up to 5,000 yd. Such a portable, electronic time interval measuring device was developed for use with a short base. This system, Dodar, will be more completely described in the sections immediately following; it may be stated here that tests with the instrument showed that it could be used in sound ranging over distances up to 8,000 yd and sometimes farther.

Equipment

Dodar.[8, 9] From its inception the communications group of the Division of Physical War Research at Duke University was concerned with the development of new sound-ranging instruments which could be used with small microphone spacings in contrast with the currently used Army systems of 2- and 4-sound-second spacings. Dodar is such a portable system for determining the direction of impulse sounds. Two or more of these units operated together will determine the direction and range. In general, two systems were studied—the Recorder Type and the Time Interval Dodar. An instrument employing magnetic tape recording was developed by the Bell Telephone Laboratories under contract with the Signal Corps Development Laboratory, Fort Monmouth, New Jersey. This instrument was tested and evaluated by the Signal Corps during the latter part of 1943, whereupon further work on it by the Division was abandoned. The Time Interval Dodar, on the other hand, was carried to completion by the Division and resulted in two models, the D-2 and the D-3, the latter being an improved model. The fundamental principles are the same for both.

Recorder Type Dodar. This system is based on the idea of recording the received signals, thereby providing the opportunity of playing them back at will and measuring the difference in arrival times. The recording is made on a magnetic steel tape arranged in an endless loop to provide repetition of the signal, thus permitting the operator any amount of time he desires

to obtain a reading. The magnetic tape, however, does not record and reproduce extremely low frequencies satisfactorily. To remedy this deficiency, a modulation type of recording was proposed such that the carrier frequency would be in the center of the optimum frequency range for recording and reproducing, thus providing an adequate frequency spectrum.

Figure 18 is a block schematic of the Recorder Type Dodar showing the required components with their functions shown pictorially below. In demodulated in accordance with standard techniques. At this point, the output waves are replicas of the original air waves, the time sequence and differences having been maintained. In listening to these two outputs binaurally, the sound will appear to come from some direction in front of the observer.

The construction of the reproducer is such that the reproducing pole pieces and, therefore, the sound may be advanced or retarded. Operation of the phasing control will produce the illu-

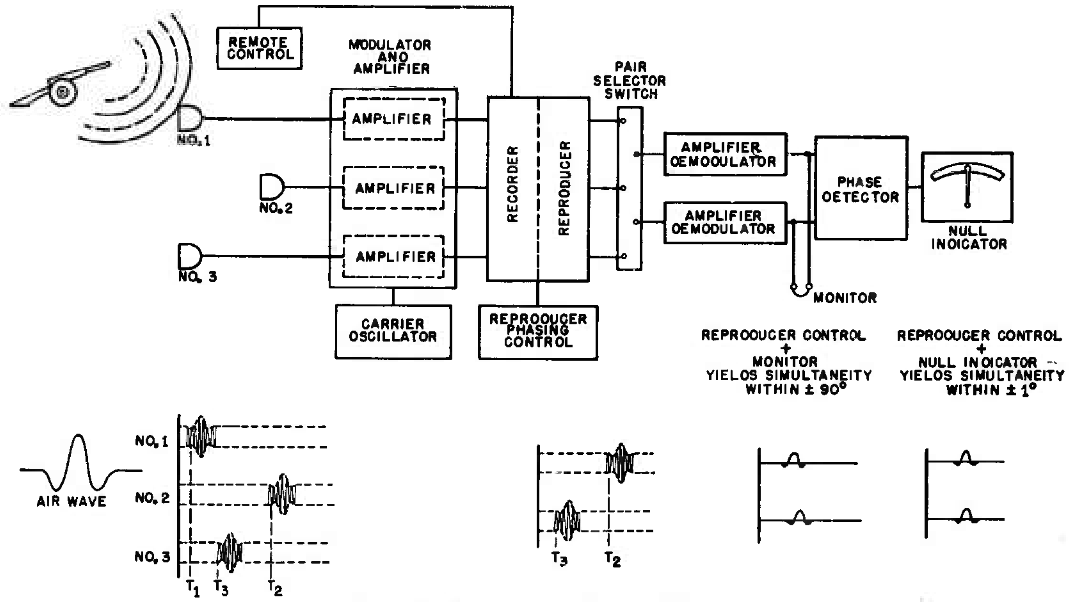


FIGURE 18. Recorder Type Dodar.

the upper left-hand corner is shown a gun with a representation of the sound wave as it progresses along and passes over microphones 1, 2, and 3. The microphone in combination with a modulating bridge circuit produces an a-m signal. The modulated carrier is amplified to produce the appropriate level for the recorder. The remote control shown feeding into the recorder is so arranged that when the operator hears the signal he is able to stop any further recording by a push button. This control automatically places the recorder-reproducer in the reproducing condition. The outputs of the three channels are then made available, two at a time, by a pair selector switch so that the time difference between any two signals may be obtained. Each of a pair of reproduced signals is amplified and sion that the sound moves around in space. The control is adjusted to make the sound appear to be immediately in front of the observer. When this occurs the signals are being applied to the ears simultaneously.[c] The wavelets shown immediately below the headphone monitor have been drawn as though such an adjustment had been made. In other words, approximate simultaneity has been achieved. A finer adjustment is made with the aid of the phase detector and its null-indicating instrument, resulting in simultaneity within 1 degree for the frequencies involved.

[c] Certain unpublished tests by the Bell Telephone Laboratories indicate that such simultaneity may be achieved binaurally well within 90 degrees of a 20-c wave.

Such precision would provide time measurements with an accuracy of about 0.1 millisecond. It was anticipated that this would permit sound ranging up to large ranges (say 5,000 yd), with microphone spacings of about 25 ft. It was further hoped that the aural perception of the operator would enable him to separate and identify several signals received in a short time period.

In general, the various components were designed to meet their individual requirements without any serious complications. However, designs for two of the components, namely the microphone and recorder-reproducer, were never satisfactorily evaluated. The type of structures used in the microphone design produced serious variations with temperature, with the result that the system could not be stabilized. However, a more serious difficulty was encountered: in the reproducing condition, the steel tape produced a rather high noise, thereby preventing the detection of low-strength signals. This limited the device to very short ranges.

Time Interval Dodar, D-2. This Dodar model was developed for the Marine Corps in connection with invasion tactics in the South Pacific. The Marine Corps set the following requirements:

1. Portability: all equipment should be lightweight, rugged, and usable in amphibious operations.

2. Personnel and transportation: equipment should be limited to a small unit, capable of being landed in the early stages of an operation.

3. Accuracy: the design should give accuracy commensurate with counter-battery fire.

The first two characteristics should take preference over any increase in accuracy beyond the point of counter-battery fire.

At the beginning it was felt that a direct-reading instrument having an inherent accuracy of 1 millisecond could be developed. A probability study was made of the errors which would be obtained with such an instrument; it was found that at a range of 5,000 yd or less, an accuracy of 200 yd would be obtained if the product of the microphone spacing d and station spacing s was set at a value of 10^6 sq ft. The study indicated that such an accuracy would be obtained at least 80 per cent of the time for azimuths not exceeding 50 degrees.

Studies made by the physical research group showed that the mean time deviation due to atmospheric fluctuations as observed at two microphones would approximate 1 millisecond if the spacing were 400 ft. If, therefore, the instrument error approximates that introduced by atmospheric variations, the design should be optimum from the standpoint that both errors are equal. It was felt, however, that the error caused by these atmospheric variations might exceed 1 millisecond, with the result that the product sd must be increased to maintain the same accuracy. Hence the basic requirement for microphone and station spacings was set at 400 ft for the microphones and 2,000 yd for the stations.

In addition to this arbitrary setting of the time accuracy required, the instrument should measure time intervals regardless of the direction from which the sound approaches the microphone sub-base, and the instrument must provide a reading sustained long enough to be read by the operator, during which period subsequent signals must not affect the reading.

Operation of the instrument may be understood by referring to Figure 19, which gives a block schematic diagram of the Time Interval Dodar; below this diagram the functions of the set are shown pictorially. In the upper left-hand corner is a picture of a gun with a representation of the sound wave as it progresses along and passes over microphones M_R and M_L. As shown in the block diagram on p. 130, microphone M_R produces an electric wave beginning at time T_1, whereas microphone M_L produces an electric wave beginning at time T_2. These waves are replicas of the wave which existed in the air, and each is amplified to produce a signal large enough to operate its associated trigger circuit. Operation of the trigger circuits results in two voltage outputs which are combined in the timing circuit to produce a rectangular pulse whose length is determined by the difference in times T_1 and T_2. This pulse is transformed by the timing circuit into a voltage which is "read" by the vacuum-tube voltmeter. The meter is calibrated to interpret the duration of this pulse and hence indicates directly the time difference

$T_2 - T_1$. Transformation of the pulse into the meter reading is made with the aid of a resistance-capacitor-relay circuit which charges the capacitor through the resistance for the duration of the pulse. Because a capacitor has the fundamental property of building up a voltage proportional to the time for which a constant current flows into it, the voltage appearing at its terminals will be practically a linear function of the time difference, provided the capacitor voltage obtained is a small fraction of the charging voltage.

Shown also in Figure 19 are the blocks representing the battery box with its associated 6-v storage battery. All necessary connections for heater and high-voltage supply are made through a single connecting cable between the box and the instrument.

The D-2 Dodar instrument weighs 26.28 lb and is 14⅞ in. long, 11⁷⁄₁₆ in. wide, and 10¼ in. high. The meter is calibrated in milliseconds with a range of ± 300. Special precautions were taken to maintain the calibration over a wide range of temperature and battery voltage. The associated microphones used with this model were T-21-B's, modified as described in Section 5.3 to give an improved high-frequency response. The battery box weighs 16.56 lb with batteries, and is 11⁷⁄₁₆ in. long, 7⅛ in. wide, and 10¼ in. high.

As a result of field trials, the Marine Corps Equipment Board suggested that the Dodars be given a trial under actual combat conditions. It requested the construction of 25 units, 20 of which were to be used by the Marine Corps in combat, while the remaining 5 were to be used jointly by the Board and the Division of Physical War Research for further testing. One of the five was delivered to the British Ministry of Supply Mission, and forwarded by them to the Larkhill Laboratories in England for tests by the Air Defense Research and Development Establishment.

It was decided to have most of the work done by outside agencies, and limit the work of the Division to the final assembly, calibration, and testing. The Airborne Instruments Laboratory, Mineola, New York, did the assembling and wiring of the instruments. The final assembly included the application of a moistureproofing and fungus-resistant finish, in accordance with the Signal Corps Specification No. 71-2202 entitled "Moisture and Fungus Resistant Treatment of Signal Corps Ground Signal Equipment (Over-all Treatment of Assembled Equipment)." Each instrument was calibrated by supplying each of its input channels with a steep wave front signal separated by known time intervals. These pulses were produced by a timer mechanism and circuit, capable of

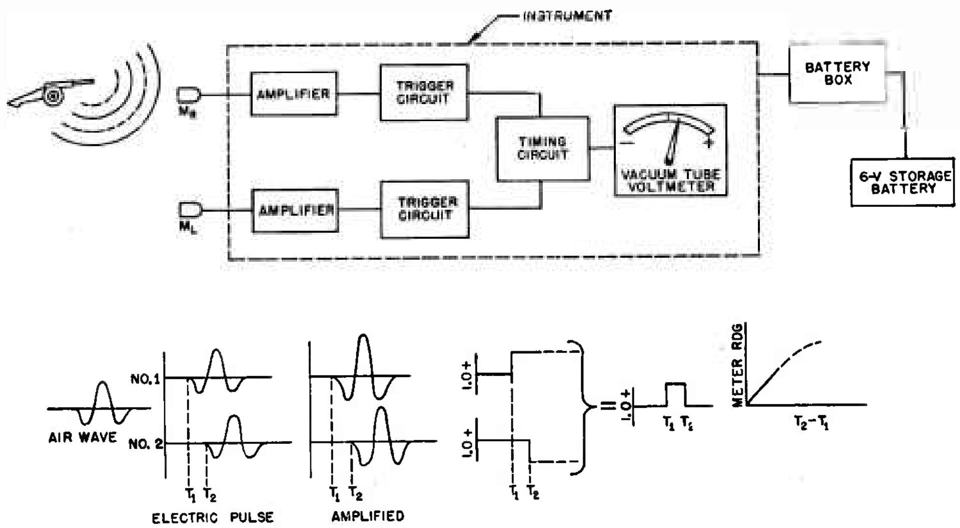


FIGURE 19. Time Interval Dodar.

cyclically producing pairs of pulses spaced at time intervals ranging from 0 to 500 milliseconds with an accuracy of better than 0.1 millisecond.

A series of field tests with the D-2 Dodar were carried out, employing both TNT and guns, first by members of the Division, and finally by the Marine Corps Equipment Board at Quantico, Virginia. In general, the tests were designed: (1) to determine the effectiveness of the Dodar as a sound-ranging instrument, (2) to check the probability studies which had been made, and (3) to determine the criteria for microphone placement and optimum meteorological corrections to be applied.

The results of the final tests are summarized in the following excerpt taken from the Marine Corps Equipment Board Report No. 192 of March 21, 1944:

CONCLUSIONS:

From the results obtained with the new Dodar sets, under favorable meteorological conditions and with a largely untrained crew, it is felt that the units with trained crews will perform in the field with sufficient accuracy for counter battery fire. It is believed the size, portability, and ruggedness of the sets, together with the relatively small operating crew, will fulfill the requirements of the Marine Corps. As shown under Results, the accuracy of the location increases with the number of readings, especially under gusty-turbulent meteorological conditions. Much judgment must be exercised by the Sound Ranging officer in evaluating the accuracy of the plots, taking into consideration the weather, range, and other necessary factors.

More specifically, using a 400-ft sub-base, a station separation of 2,000 yd, and ranges between 4,000 and 10,000 yd, the final tests gave:

83 per cent of the locations within 200 yd;
74 per cent of the locations within 150 yd;
44 per cent of the locations within 100 yd;
22 per cent of the locations within 50 yd.

Other points brought out by the tests are discussed under *Handling the Data*.

The Dodar was placed in operation by the Marine Corps in combat areas with varying degrees of success. The most successful performance was in the Iwo Jima campaign, during which, according to a report of a combat officer to Headquarters, 13th Marines, 5th Marine Division, dated April 18, 1945, Dodars were used and "a total of 54 definite enemy guns and mortars were located and 90 additional unverified plots and directions were relayed to the counter battery officer . . . Dodars were found very useful during this campaign, despite many handicaps."

Improved Time Interval Dodar, D-3 (U. S. Signal Corps AN/PNS-1). The D-2 model was developed primarily for the U. S. Marine Corps for use as an experimental gun locator, with a range of approximately 5,000 yd. However, the Field Artillery Board also made extensive tests on this model, which are reported in their test number S-49-L Item No. 722-A File No. 413.684. This report indicated that the instrument was desirable and suggested it be adopted for use by Field Artillery Observation Battalions for location of mortars and light artillery. The following modifications were recommended: (1) improvement of the construction of the set to further ensure its watertightness and buoyancy, (2) provision of a frequency-selector control to adapt the instrument's frequency response to the received signal, (3) provision of a light to illuminate the meter dial during darkness, and (4) provision of a power supply to replace the dry batteries, if time permitted.

In addition to these recommendations, the field tests on the D-2 and the experience associated with its manufacture indicated the need for additional development. A program was prosecuted which resulted in a laboratory model incorporating all the features recommended by the Field Artillery Board except the vibrator power supply, and the following additional improvements recommended by members of the Division: (1) elimination of tube selection by the use of a newly developed relay and improved types of tubes, (2) use of a meter with a precalibrated scale, (3) improved resistance to excessively humid conditions, (4) increased stability, and (5) increased sensitivity.

The D-3 Dodar instrument is about the same size as the D-2 model, which it somewhat resembles, both models being based on the same theory of operation; however, the D-3 Dodar incorporates the improvements listed in the last section. The major changes in mechanical design were the use of stainless steel for fabrication of the instrument and battery box, and a change in the panel layout to provide for changes in type and location of controls. Figure

20 shows the Dodar instrument and associated equipment (cases, batteries, and leads). Figure 21 gives a closer view of the instrument panel.

Stainless steel, $\frac{1}{32}$ in. thick, was used for both the instrument and battery box in place of the $\frac{3}{32}$ in. aluminum alloy used in the older model. This was done to provide a better type of construction and ensure the case's being watertight. No appreciable difference in weight resulted from this change. Although this case was developed primarily for the Dodar, the

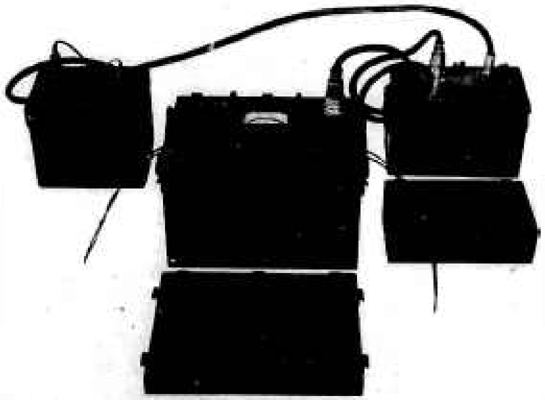


FIGURE 20. D-3 Dodar instrument and associated equipment.

design is applicable to many types of portable instruments. It satisfies the military requirements, namely, that it (1) must be portable, (2) must float with the apparatus enclosed, (3) must withstand when closed immersion under six feet of water, and (4) must be rain- and fungus-proof when uncovered for use.

An important principle used in the design of the cases was the method of obtaining a watertight seal with a rubber gasket, which involves enclosing the rubber so completely that under the pressure of the seal it cannot cold flow and thereby relieve the desired pressure. It was also found necessary to reinforce the cases at all points where outside hardware is attached.[11]

After the laboratory model of the new Dodar was exhibited to members of the Field Artillery Board, it was decided to procure finished models of the new unit in the shortest possible time. Therefore, Duke University was authorized on October 10, 1944, to manufacture units of the new model under "crash procurement." A total of 100 units was made and distributed as follows: 65 units, U. S. Signal Corps (60 of these units were for use by the Field Artillery, the remaining 5 units for standardization tests by the Signal Corps); 25 units, U. S. Marine Corps; 2 units, British Ministry of Supply Mission, on a previously unfilled order; 8 units, Duke University. These eight units were for cooperative tests by Duke University with the Field Artillery Board and the Marine Corps Equipment Board.

The facilities of Duke University were not adequate for producing 100 units. Arrangements were made, therefore, to have the major part of the manufacturing, testing, and calibration done by the Altec Lansing Corporation of Hollywood, California. Certain critical parts requiring special testing were purchased by Duke University, tested, and shipped to them. Engineers from the Division visited Altec Lansing to assist in the development of the testing procedures and to train their engineers in the method of factory calibration. A time interval generator developed by the Division was furnished for use in calibrating the Dodars.

The final acceptance tests on the new Dodar were started by the Field Artillery Board at

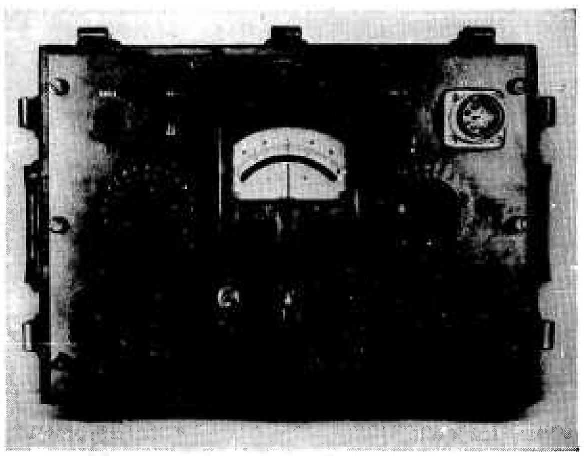


FIGURE 21. D-3 Dodar instrument panel.

Fort Bragg and completed by the Field Artillery School at Fort Sill, Oklahoma. These tests determined the ability of the Dodar to function as a sound-ranging instrument from the stand-

point of its durability, accuracy, range, and tactical use. The results of these tests indicated that the accuracy of the Dodar was satisfactory, that it was adequately protected for military use, and that it was capable of locating field artillery pieces, mortars, machine guns, and small arms fire. The accuracies of all verified sound-ranging locations made in these tests are shown in Table 2.

TABLE 2

Error in location	Per cent of total locations
Less than 50 yd	26
Between 50 and 100 yd	32
Between 100 and 150 yd	19
Over 150 yd	23

A total of 53 locations was made during the two periods of field testing from approximately 300 recorded sounds from these locations. Weapons successfully located under favorable conditions, with maximum distances (measured from an inner sub-base) at which locations were made, are shown in Table 3. These are probably not the greatest possible ranges under most favorable conditions.

TABLE 3

Weapon	Distance (yd)
60-mm Mortar	3,000
81-mm Mortar	5,000
4.2-in. Mortar	4,500
Battery of .30-cal machine guns	4,500
.50-cal machine guns	4,500
Rifles and carbines	2,000
Anti-tank rocket launcher	4,100

Time did not permit extensive combat use of the D-3 Dodar before the end of World War II. Although used in the Okinawa campaign it was not reported on very favorably. However, it is felt by members of the Division and by Marine Corps personnel most familiar with the Dodar that it was not given a fair test on Okinawa and that it is capable of a much better showing.

Ultralightweight Dodar System. In the interests of reduced size and weight, as well as reduced susceptibility to damage from water, dirt, etc., a new lightweight crystal microphone was developed by the Division. This microphone is described in the next section. At the same time a breadboard model of a vibrator power supply which could be mounted in the battery box was developed. The weight of this box with the vibrator power supply is less than with the original four "B" batteries, and the new microphone weighs 4 lb as against 24 lb for the T-21-B. A demonstration of a complete Dodar system employing the improved D-3 instrument, the new crystal microphone, and the model of a power pack was conducted by members of the Division for representatives of the Marine Corps Equipment Board and the Marine Corps Field Artillery School at Quantico, Virginia. The results of this test indicated that the overall sensitivity of the new microphone (designated the T-1) and Dodar was greater than the old combination of the T-21-B modified microphone and Dodar. When the proper frequency band was selected, there was a substantial improvement in signal-to-noise ratio. Thus it was possible to range on guns located beyond 5,000 yd in the presence of noise due to airplanes, trucks, and wind which would have made sound ranging impossible with the T-21-B and Dodar setup. It was also noted that there was less necessity of checking the field calibration of the Dodar when the vibrator power supply was used. Termination of the Division's contract prevented further development of this system.

New Lightweight Crystal Microphone.[14, 21] The principal energy contained in sound waves from field artillery guns and howitzers lies in the region from 5 to 40 c. Substantial components, especially in the case of the smaller field weapons, may reach values as high as 100 c. Sound ranging has, therefore, required the design and use of highly specialized microphones particularly suited to the efficient reception of frequencies within this region.

The reduction of the effects of wind and other extraneous sounds, which frequently cause severe disturbance in the upper portion of this frequency band, has led to the use of relatively sharp cutoff, low-pass filters in microphones. Filters for such low frequencies, whether electric or acoustic, have in turn resulted in large, heavy microphones which are quite unsuitable for highly portable use.

The need for a reliable, small, lightweight microphone for sound ranging became apparent

during the development of Dodar (AN/PNS-1). The choice of microphone available for use with Dodar was limited to two types normally utilized for general sound ranging but each of these has serious disadvantages.

The T-21-B condenser microphone has been the standard Service model since 1941. It is large, heavy, and very cumbersome to carry (see Figure 22). Because its case is a part of the electric circuit, the microphone must be

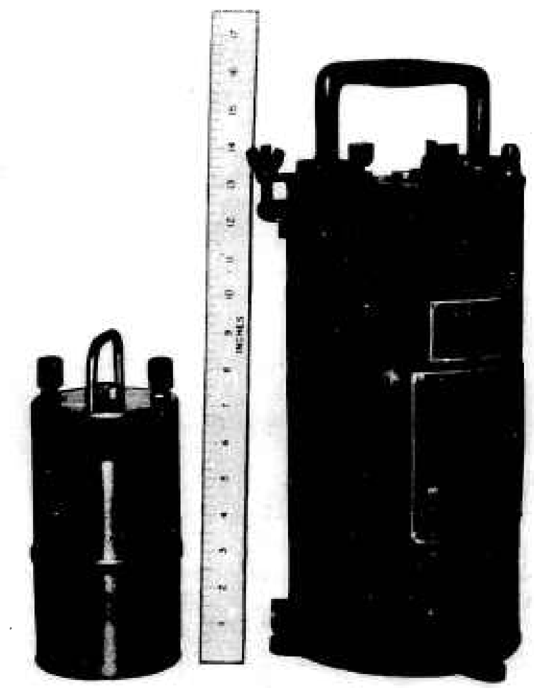


FIGURE 22. Comparison of T-1 microphone (*left*) and T-21-B modified microphone (*right*).

enclosed in a heavy rubber boot when in use. In addition to its physical inconvenience, the T-21-B is subject to failure through entry of foreign material. This fault was minimized but not avoided in the modification described in Section 5.3.

The T-23 hot wire microphone, which is somewhat smaller and significantly lighter than the T-21-B, is the newest Signal Corps type and only recently was adopted as the standard replacement. Production delays, however, made it unavailable until after World War II. In addition to its unavailability in large numbers, its use with Dodar was prohibited by its extremely short filament battery life. Both types of microphones are subject to serious damage from temporary submersion, which is a frequent occurrence in field operations.

In addition to being designed for Dodar in particular, it was anticipated that a new, highly portable microphone might be designed to contain features which would make it superior to other microphones for general sound ranging. Such characteristics as ability to withstand temporary submersion, a convenient means of selecting several upper frequency cutoffs to suit particular sound-ranging conditions, and ease of maintenance without exposing vital parts are desirable for all sound-ranging purposes.

The following requirements were considered.

1. The highly portable microphone should be as small as possible—preferably of a size permitting its being carried by pocket.
2. It should be as light as possible—preferably under 5 lb.
3. It should be capable of operation with its case in contact with the ground.
4. Its filament battery life should be increased as much as possible over present types.
5. The highly portable microphone should be capable of use in circuits designed for T-21-B and T-23 microphones.
6. It should have approximately the same sensitivity and power output capacity as the T-21-B microphone.
7. It should have conveniently selectable, upper frequency cutoffs permitting its use for ranging on all sizes of field artillery weapons with the maximum elimination of extraneous noise. The frequency ranges set ran from 3 to 40 c, from 3 to 60 c, and from 3 to 80 c.
8. The microphone must be capable of satisfactory operation over a temperature range of from 0 to 120 F and should not be damaged by extended exposure to temperatures of 160 F. The effects of humidity on the microphone should be minimized.

Two models of the highly portable microphone were developed: an experimental model T-1 and a model T-2 for combat use with Dodar.

Five T-1 microphones were constructed and

subjected to extensive laboratory and field tests. They were then turned over to the Camp Evans Signal Laboratory of the Signal Corps and to the Field Artillery Board.

At the conclusion of these acceptance tests the improvements anticipated from the Division tests and those resulting from the Service ac-

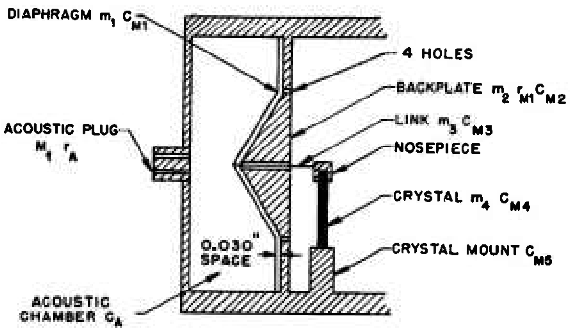


FIGURE 23. T-1 Crystal microphone—analogous circuit of transducer and acoustic filter.

M_1 = Acoustic inertance of filter plug
r_A = Acoustic resistance of filter plug
C_A = Acoustic capacitance of filter chamber
m_1 = Mass of diaphragm
C_{M1} = Compliance of diaphragm
C_{M2} = Compliance added to diaphragm by acoustic backplate
m_2 = Mass added to diaphragm by acoustic perforations in backplate
r_{M1} = Resistance added to diaphragm by acoustic perforations on backplate
C_{M3} = Compliance of link
m_3 = Mass of link and nosepiece
m_4 = Effective mass of mounted crystal
C_{M4} = Compliance of crystal
C_{M5} = Compliance of crystal mount.

ceptance tests were combined in the design of a combat model, designated Type T-2. Based on the performance of the Type T-1 microphone and the modifications, the T-2 model was accepted for use with Dodar (AN/PNS-1) and was given the Signal Corps nomenclature M-12 ( )/TN.

Ten Type T-2 microphones were constructed, submitted to tests by the Division, and turned over to the Armed Forces prior to the close of the contract. Information pertinent to manufacturing specifications and a complete set of manufacturing drawings of this model were submitted to the Camp Evans Signal Laboratory.

A further modified model of this microphone, taking into account its use with current standard and with anticipated sound-ranging apparatus, was authorized as Signal Corps Type M-13 ( )/TN. The closing date of the contract did not permit the completion of this model.

The T-1 and T-2 microphones are of a crystal type, utilizing a recently developed piezoelectric crystal of ammonium dihydrogen phosphate. This crystal is capable of withstanding temperatures up to 212 F without loss of its piezoelectric properties, as compared with 130 F for the best previous types suitable for use in sound-actuated microphones.

The crystal is contained in a small metal enclosure (see Figures 23 and 24) which serves to protect it from damage due to handling. The crystal is cantilever mounted, its free end being actuated by a link bar which attaches it to the center of a formed aluminum diaphragm (0.002 in. thick). The crystal, or under, side of the diaphragm is protected by a backplate spaced 0.030 in. from the diaphragm, providing acoustic damping for the system and serving to support the diaphragm should water invade the upper acoustic chamber.

The microphone contains a two-stage resistance-coupled amplifier (see Figure 24). Material reduction in size was accomplished by the use of miniature tubes.

The frequency response of the T-1 microphone is obtained by means of two types of low-pass filters: (1) an acoustic filter and (2) an amplifier interstage filter. The latter is adjustable in three steps by means of a simple terminal switch, making available three separate frequency ranges.

The physical dimensions of the T-2 microphone (10 in. high with a 4⅝-in. diameter) and its operating weight of 4 lb enable it to be carried by pocket or hand as circumstances dictate. Many features were incorporated in its design to ensure reliable operation and convenient maintenance under field conditions.

The new lightweight crystal microphone satisfies all the requirements and has a much reduced susceptibility to moisture, dirt, etc. Tests indicated that no serious damage results from complete submersion for at least 12 hours in depths experienced in normal field operations. Convenient maintenance is possible without exposing any of the critical parts of the micro-

phone. The overall frequency response of the new microphone for each of the three ranges is shown in Figure 25. For the microphone alone, the ranges (10 db cutoff) were found to be: Range H, 4-80 c; Range N, 4-60 c; Range L, 3-40 c. The recommended use of the ranges is as follows:

Range H—for ranging on small field weapons, such as mortars and light artillery, where extraneous noise permits;

Range N—for general sound ranging;

Range L—for ranging under conditions of extreme extraneous noise when the signal has sufficient energy at very low frequencies to give a usable output.

Field response tests proved the advantage of the high-frequency range H for ranging on small weapons and for distinguishing the ballistic wave from the muzzle wave. Figure 26 is an actual record of a 60-mm mortar, in which the middle trace (third from bottom) shows the response of the T-1 microphone on Range H. The response to the low frequencies produced by large weapons was found equally good as that of the T-21-B or T-23 microphone. In these tests the new microphone compared favorably with the older types from the standpoint of extraneous noise and ground vibration. Further additional improvements in the design were recommended by the Division, but time did not permit further development.

5.4.2 Handling the Data

Systems of Coordination

In the multiple-short-base method of sound ranging for which the Dodar system was developed, consideration must be given to the best method of coordinating the sub-bases employed (usually three). It is important that this coordination be good to ensure that each Dodar set is ranging on the same gun at the same time and to reduce the time required for the subsequent plotting and relaying of the determined plot to the counter-battery officer. There are two systems of coordination possible: (1) to locate each Dodar instrument near its corresponding microphones and to connect the operator of the instruments with sound central by wire or radio and (2) to locate all the Dodar instruments at sound central.

There are advantages and disadvantages to each of the two systems listed. In the first system, the observer is nearer the microphones should they require repair; if in front of them,

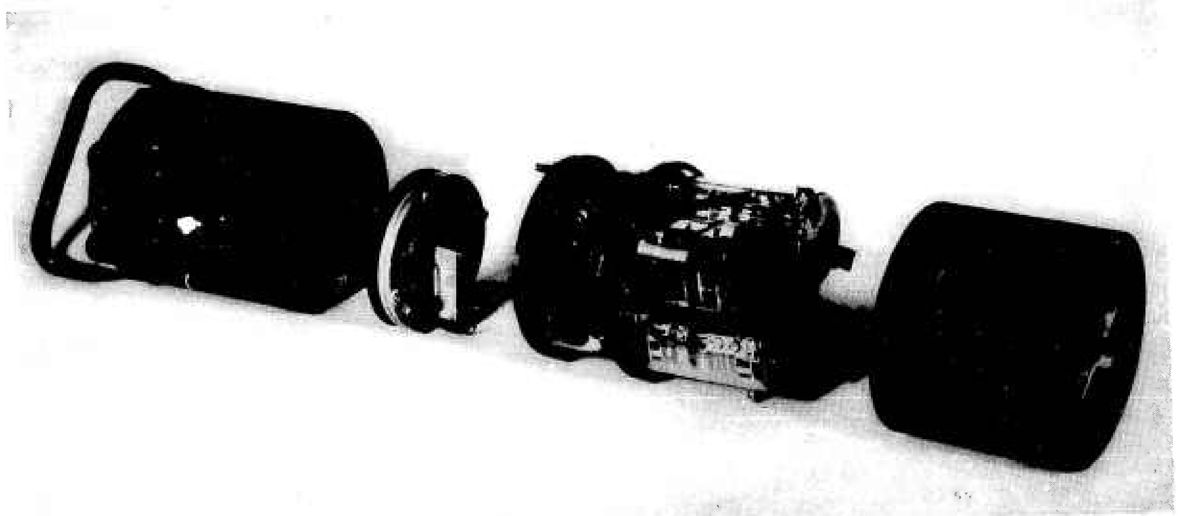


Figure 24. T-2 Microphone.

he may be able to pick out the desired gun pulse by ear, but both the observer and instrument may be in a more exposed position. In the second system, observers and equipment may be more protected and results obtained from each Dodar set may be more readily compared and plotted; but longer lines between microphones and instruments increase the probability of a set becoming inoperative through a line being broken or microphone damaged, and repair of such damage would require more time. It was concluded by the Division that the choice of system could best be decided by actual combat experience, and

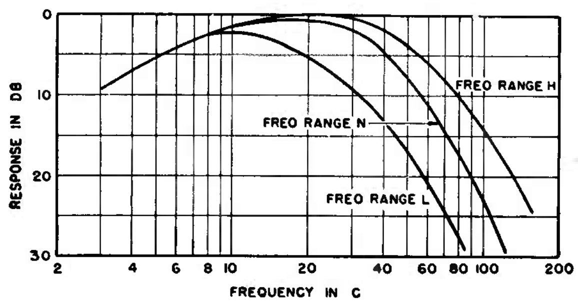


FIGURE 25. Overall frequency-response curves for T-1 microphone.

the matter was left up to the Marine Corps. At the end of World War II a conclusive answer to the problem had not been received.

PROBABILITY OF GUN-LOCATING ERRORS[8]

Analytical Study. An analytical method was developed for evaluating the probability of locating a target when two direction lines with their angular errors and the spacing between their origins are known. The method is based on probability and geometrical principles. It was found that there is a probability p that the location will lie within an ellipse whose major axis gives the value of the range error and whose minor axis gives the bearing or line error. The range error δR is large compared with the line error δL and is therefore the only one which need be considered in determining the location accuracy. The expression for δR is

$$\delta R = 0.775 \frac{V_H \delta(\Delta t) R^2 \sqrt{h}}{sd \cos^2 \theta}$$

where

V_H = velocity of sound,
$\delta(\Delta t)$ = error in arrival time interval,
R = range,
s = distance between centers of the two sub-bases,
d = length of each sub-base,
θ = azimuth of source measured from normal to base,
$h = \log_e \frac{1}{p}$.

It will be noted that δR is directly proportional to R^2 and inversely proportional to the product sd. The accuracy is best for small azimuths. Figure 27 shows the error in range as a function of azimuth for a time interval error of 2 milliseconds and an sd product of 2.4×10^6 sq ft, values which approximate field conditions for the Dodar.

In preliminary field tests of the Dodar conducted at Quantico, Virginia, a microphone base of 400 ft and a separation of 2,400 ft were used, giving an sd product of about 10^6 sq ft. Calculated and observed errors agreed well even though the number of shots was small. The proportionality between δR and R^2 was found to hold. In the final field trials of the Dodar the sd product was increased to about 2.4×10^6 sq ft by increasing the station separation to about 2,000 yd. The results have been summarized previously. The variation of probability with range error is consistent with theory. In conclusion it may be noted that the Army, in its field manual (FM 6-120) covering the Dodar, recommended that the distance between flank sub-bases be about half the distance from the base to the target area, making the angle subtended by the outside microphone sets about 500 mils (6,400 mils equal 360 degrees).

REDUCTION OF ERRORS DUE TO METEOROLOGY AND TERRAIN[8, 10]

In sound ranging with Dodar, corrections must be applied for temperature and wind; the effects of terrain must also be considered. Furthermore, fluctuations in meteorological conditions will affect the time intervals to be measured in a random way for which it is hard to correct. When smaller microphone separations with resulting smaller time intervals are used, the effect of meteorological fluctuations

is relatively more important. Conversely, a Dodar system may be used to study such variations.

Temperature. The effective temperature taken by the Army for Dodar sound ranging is the same as that for long-base sound ranging (see Section 5.2). The Marine Corps uses the surface temperature.

Wind. In the Dodar field tests, a study was made of the effect of wind. It was found that a simplified wind correction could be used for the smaller ranges covered by the Dodar instead of the more complex "standard" correction used by the Army. It was found that the optimum wind correction is given by the 45-second observations on a rising balloon in the wind. The Army has adopted the first-minute wind as the effective value, while the Marine Corps has chosen to use the 30-second wind observation for ranges less than 7,000 yd, the one-minute observation for ranges over 10,000 yd, and the correction yielding the smallest triangle of error for intermediate ranges.

Terrain. The effect of the terrain in which the microphones were located was found to be an important factor, but one hard to correct for. To minimize this effect the following rule was laid down: both microphones of each Dodar sub-base should be located in similar terrain. Microphones should also be kept away from the edge of a wooded section. The best location for the microphones was found to be in holes on the crest or forward slope of a hill.

"Met" Fluctuations. It is obvious that any system of sound ranging based on airborne signals will be adversely affected by motion of the transmitting medium or local variations in the transmission properties of the sound path. Corrections may be applied to neutralize errors produced by constant meteorological conditions, but variations in the meteorology have not as yet been mastered. This is a serious weakness in gun ranging by sound. In this connection some hopeful beginnings were made. The physical research group observed that a relationship appears to exist between variations in the amplitude of the signals received by two microphones and the associated time differences. The value of such a relationship lies in the fact that its use permits corrections to be made for the variations in meteorological conditions without the onerous, if not impossible, measurement of the micrometeorological conditions. Hence, a peak-reading voltmeter was developed to measure amplitudes received during Dodar operation. The resulting tests will be discussed in the next section, but it may be stated here that a high degree of correlation between variations

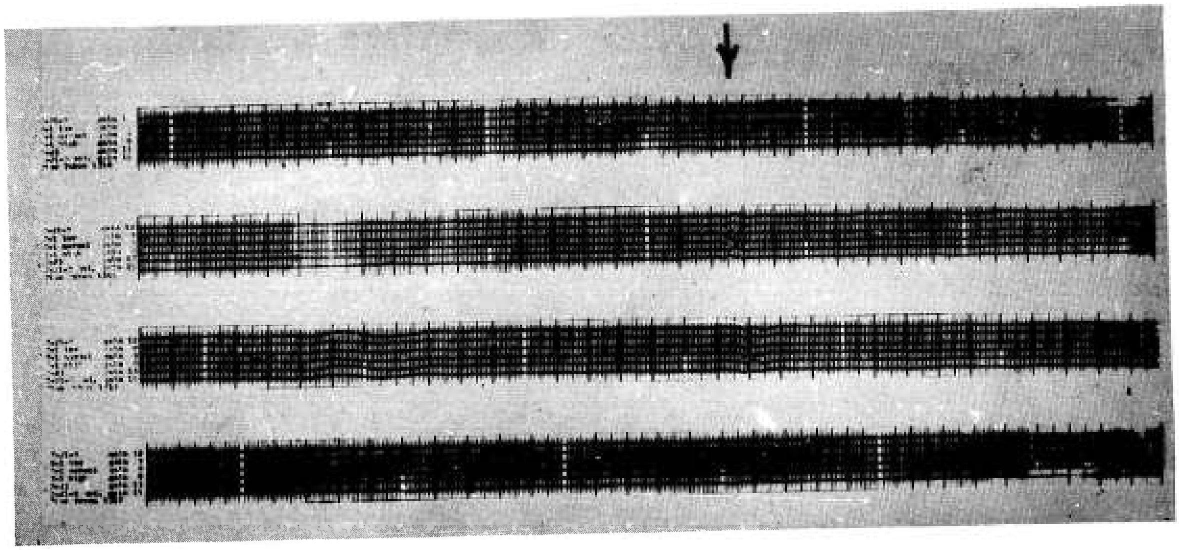


FIGURE 26. Records of actual guns using various types of microphones.

in amplitude and arrival time of a sound impulse at a given microphone appears to exist, and that a material improvement in sound-ranging accuracy may be obtained by an application of this correlation.

5.5 SOUND TRANSMISSION THROUGH THE ATMOSPHERE[2, 5, 10]

The physics of the propagation of sound energy through the atmosphere and along a boundary, such as the ground, is fundamental to the problem of correcting for acoustic gun-ranging errors, particularly those due to "met" and terrain conditions.

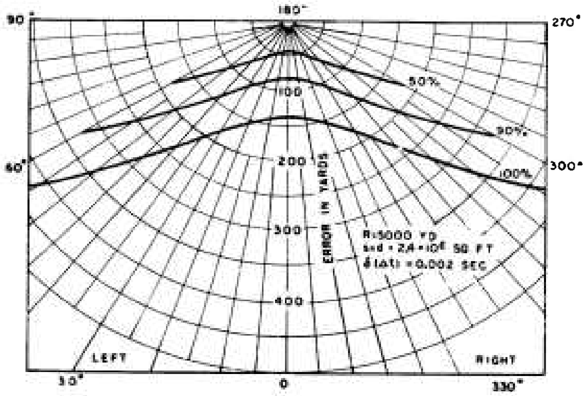


FIGURE 27. Probable range error vs azimuth.

In spite of the fact that this study constituted a pure research problem of rather long duration, a section of the Division was assigned to the problem. The reasons were twofold: (1) the only method of improving sound ranging, should certain empirical methods fail, might be expected to come through the complete understanding of the physics of sound propagation; and (2) it was believed that a fundamental knowledge of sound propagation would be of real value, particularly if World War II lasted a long time.

Two lines of procedure were planned for the solution of the problem. The first was an empirical study of the possible relationships existing between errors in gun ranging and such meteorological measurements as could be made. The second was a basic physical study, both experimental and theoretical, of sound transmission through the atmosphere. At times the order of procedure and the nature of the experiments to be performed were decided on the basis of their possible value to sound ranging rather than on their value to the fundamental research. Every attempt was made to reduce this interference with pure research to a minimum.

Considerable exploratory experimental work was done. Several lines of attack were followed, a considerable amount of data was amassed, and some theories to account for these facts evolved; however, the problem is far from completely solved. In some respects the work appears to be merely a collection of disconnected experiments, but it is believed that the resultant experimental data constitute a good starting point for further research, and they are, therefore, presented in spite of the fact that the work was discontinued before their full significance could be determined.

5.5.1 General Background

Types of Errors in Sound Ranging. In locating a gun by sound, consideration must be given to the possible sound rays through the atmosphere from the gun to the receiving microphones and to the velocity of sound along such rays. Furthermore, the sound rays in this case are generally confined to relatively low altitudes (sometimes practically to grazing incidence); hence the effect of the presence of a boundary, such as the ground, must also be considered. Errors in sound ranging fall into two classes: instrumental errors and propagation errors. The techniques of and the equipment for acoustic gun ranging are sufficiently advanced so that the instrumental errors are smaller than the propagation errors, except on those few days when ideal conditions exist, when the latter decrease to approximately the same order of magnitude as the instrumental errors. Therefore, the propagation errors, mainly due to meteorology, become the most important errors to eliminate.

Macromet vs Micromet. The errors in sound ranging due to wind and temperature have been

found to be of two types. First, there are those errors due to the overall and slowly changing meteorological conditions of the atmosphere, hereafter referred to as the macromet, or just the "met." Second, there are those errors due to those meteorological factors which vary rapidly and in a random manner with regard to both space and time, hereafter referred to as the micromet.

Corrugations. The problem may be stated in a slightly different way. If the atmosphere possessed horizontal homogeneity, and wind and temperature gradients were not changing with time, the acoustic wave fronts traveling out from a sound source would be regular in form, becoming approximately a plane wave at relatively great distances from the source. However, if meteorological or terrain conditions vary in an irregular manner from place to place, or if wind and temperature fluctuate rapidly with time, then one would expect the acoustic wave fronts to possess an irregular shape. The resulting irregularities are sometimes referred to as *corrugations* or *serrations*. Such corrugations would, of course, affect the arrival time at a given microphone of the sound impulse from a gun, or the difference in arrival times measured for a pair of microphones.

Correcting for the "Met." The existing methods of correcting for the effect of meteorological conditions (Section 5.3) assume in every case that conditions in the atmosphere are practically steady, that is, that wind and temperature do not change appreciably in the interval between the taking of meteorological observations and the application of the corrections computed from them. Furthermore, it is assumed that conditions, characterized by a single set of vertical soundings, are the same for all the microphones of the base. For this reason these methods may be said to attempt to correct only for the macromet. In practice the hope is either expressed or implied that this is good enough. However, on the basis of a study of the effectiveness of the standard method and subsequent work performed by the Division, this appears to be too optimistic. In undertaking this project it was felt that it was necessary to determine: first, how important micrometeorological factors are in sound ranging; and second, if such factors are important, whether any method of correcting for them could be found.

5.5.2 Experimental Procedure

After a considerable study of microphone arrays and consultations with members of the Field Artillery Board, Fort Bragg, North Carolina, and the Marine Corps Equipment Board, Quantico, Virginia, two types were chosen for study by the Division of Physical War Research. The first was the Army straight-base system. The second was the employment of two or more short-base direction finders, suitably coordinated (the Dodar system).

A statistical study of the effectiveness of the standard method of applying a meteorological correction when using the straight-base system was made. In this study data were acquired under field conditions at Fort Bragg, North Carolina, and at Fort Sill, Oklahoma.

Work on the reduction of errors due to the macromet included the following: (1) a comparison of various types of microphone bases, (2) an investigation of the possibility of improving the methods of evaluating the macromet data, (3) a comparison of the various methods of correcting for the macromet, and (4) a proposed method of sound ranging eliminating meteorological corrections.

The investigation of the effect of wind and temperature fluctuations in the atmosphere on sound propagation formed a large part of this work. The method employed sources of both steady, single-frequency sounds and sound impulses. With single-frequency sounds, amplitudes and relative phases were measured at pairs of microphone receivers, while with the impulse sounds, amplitudes and arrival times were measured at the microphones.

Although impulse sound measurements provide the most direct approach, it was deemed advisable to carry on a parallel study of the transmission of continuous sound from a single-frequency, sine wave source for the following reasons.

1. Gun sounds are made up of a complex combination of frequencies, which vary with

the caliber and charge of the gun, and also from gun to gun and from one round to another. Analyzing data on impulse sounds is considerably more difficult than analyzing similar data on steady-state sounds.

2. The number of readings in a given time period is limited by the rapidity of loading and firing a gun, or of placing explosive charges. It is sometimes desirable to get closer grained sampling with respect to time. With phase measurements of sustained, single-frequency sound, these readings may be made continuously at intervals corresponding to the period of the signal.

3. Gunfire and explosive charges are relatively expensive, requiring special equipment and trained personnel not readily available for a continuous, extended study at different locations.

Measurements with Single-Frequency Sources. Two microphones were placed at various fixed positions in front of a continuous sound source emitting a single frequency. The amplitude and phase of the sound at each microphone were recorded either continuously or at regular intervals of a few seconds. If the two microphones are equidistant from the sound source, then, in the absence of wind, horizontal inhomogeneities, or unsteady conditions, one would expect the amplitude and phase at the two microphones to be the same. Presence of a steady wind or irregularities of terrain should produce a steady difference in phase at the two microphones; whereas if the wind is gusty or the atmosphere possesses pockets of hot or cold air carried by the wind, one would expect momentary fluctuations in the phase difference as well as in the amplitude at each microphone. Actually, the phase difference and the two amplitudes were observed to fluctuate continuously. During these experiments various meteorological elements such as wind speed, wind direction, and temperature were simultaneously recorded.

The fact that the fluctuations appeared to follow a normal random distribution suggested that it might be advantageous to apply statistical methods. Since a phase difference between two microphones is equivalent to a difference in arrival times for a given portion of the wave front, it is similarly correlatable with a difference in arrival times for impulse sounds such as are encountered in sound ranging. Hence fluctuations in phase difference and dependence of mean phase difference on various factors were studied in these experiments for the purpose of estimating and possibly reducing errors in sound ranging due to micrometeorological factors. To this end experiments were performed under a variety of conditions. The effect of a variation in one condition at a time was investigated, so far as possible, as follows: (1) changing the source from a point on the perpendicular bisector of the microphone base (the usual position) to a point in line with the microphone base, (2) varying the separation of the microphones, (3) varying the distance between the microphones and the source, (4) varying the frequency of the source, (5) varying the time of day of the experiment, (6) choosing times when wind speeds and gustiness were as desired, (7) choosing times when wind gradients were as desired, and (8) choosing times when temperature gradients were as desired. It was frequently impossible to get the conditions of (6), (7), and (8) as desired.

Although the microphones in the above experiments were kept in a horizontal line on the ground, it became evident in studying the effect of wind and temperature gradients that the investigation would not be complete without including experiments in which one microphone was raised vertically above the other. For this purpose a 50-ft mast was employed; measurements were made of amplitude and phase as a function of the height above the ground and of the relation of this structure to (1) wind gradient, (2) temperature gradient, and (3) nature of the terrain.

Measurements with Impulse Sources. The results of the experiments are summarized later; it may be said here that a much better understanding of wave front corrugations, of micrometeorology, and of sound propagation along a boundary was obtained. However, in order to apply these results to the problem of reducing short-period errors in gun ranging, it was felt advisable to relate these experiments to others in which impulse sources of sound approximating gunfire and actual sound-rang-

ing bases and recording equipment were used.

It should be stressed that short-period fluctuations in the atmosphere make it useless, except under the most favorable conditions, to read arrival times to closer than a few milliseconds, and that the resulting error becomes much more important when a short base is used, for then the time difference itself is small. This applies in particular to the Dodar, where the length of the base is usually between ⅓ and ½ sound-second. Therefore experiments were performed in which Dodars as well as the standard GR-3-C equipment were used.

The various "shoots" during which sets of data were obtained may be summarized as follows.

Date	Place	Source	Recording Equipment
5-20-43	Fort Bragg	TNT	GR-3-C
7-23-43	Fort Bragg	240-mm Howitzer	GR-3-C
7-29-43	Fort Sill	105-mm Howitzer	GR-3-C
5-29-44	Fort Bragg	155-mm M-1 Gun	GR-3-C and Dodars
5-30-44	Fort Bragg	155-mm M-1 Gun	GR-3-C and Dodars
7-10-44	Quantico	TNT and dynamite	Dodars
7-19-44	Quantico	TNT and dynamite	Dodars
1-8- 45	Fort Bragg	TNT and mortars	GR-3-C and Dodars
1-10-45	Fort Bragg	TNT and mortars	GR-3-C and Dodars

During these experiments, as in those with a single-frequency source, the effects of variations in the following were studied: direction of microphone base, microphone separation, distance of source, meteorological conditions, and nature of the terrain.

Comparison of Impulse and Single-Frequency Measurements. Certain characteristics peculiar to single-frequency measurements required care to be used in comparing the results of the single-frequency and impulse measurements.

There may be a difference under certain conditions between phase velocity, measured in the single-frequency studies, and signal velocity, given by impulse measurements. Because of interference phenomena, multiple arrivals, and other factors, these records may not be interchangeable.

It has not been possible to obtain a practical high-intensity source of sustained single-frequency sound in the low-frequency range (5 to 50 c) in which important parts of the energy of gun sounds exist. It is thus necessary to extrapolate over a rather wide frequency range. The lowest frequency used in the single-frequency studies was 50 c, and most of the work was done between 100 and 400 c.

Even at higher frequencies it is impossible to secure a sustained source of sound with peak pressures comparable with those encountered in gun sounds.

A two-port siren designed to produce 2.5 kw was used in some of the studies described in this report, at a maximum distance of 1,600 yd. Sound ranging in military operations is usually conducted over ranges from 3,000 to 30,000 yd. Impulse measurements were made, however, in connection with this project as close as 1,200 yd, resulting in some overlap.

It should be borne in mind that under some conditions the sound path traversed in long-distance transmission may be considerably different from that encountered in shorter ranges.

5.5.3 Experimental Equipment

Single-Frequency Measurements

Several methods of measuring phase and amplitude of a single-frequency source were used. The most recent and complete system is shown in simplified form in the block schematic (Figure 28).

The slow-speed oscillograph showed records directly on waxed paper, and gave plots of phase change and amplitude at a number of microphones as a function of time. The equipment contained more elements than are shown in Figure 28. A complete duplicate of the equipment shown could be set up, giving the amplitudes at four microphones and three phase differences, representing any desired pairs of signal inputs (one input, if desired, could be from a common reference microphone or the input to the speaker).

Sound Sources. Two loudspeakers were used: (1) a two-section re-entrant horn with an opening about 5 ft square and a cutoff frequency of 50 c and (2) a stereophonic horn system loaned

to the Division through the courtesy of the Bell Telephone Laboratories.

The 5-ft horn gave an acoustic output of 85 db above 10^{-16} watts per sq cm at 100 yd, using a frequency of 200 c. The larger horn gave an output 8 to 10 db higher at this same frequency. With both systems type 200-DR Hewlett Packard oscillators were used.

Two sirens, developed by the Bell Telephone Laboratories and built by the Chrysler Corporation, were used during these studies. One was driven by a 10-hp gasoline engine, and the other by a 10-hp electric motor powered by a 10-kw diesel-driven generator. The siren provided a signal level for equal distances approximately 26 db higher than that available with the 5-ft horn, but introduced problems caused by poorer frequency stability, greater complexity of wave form, and less flexibility of frequency choice.

Microphones. Conventional microphones were used, with dynamic types preferred on the grounds of ruggedness and relatively permanent calibration in field use. Most of the measurements were with Western Electric type 633-A transmitters, although WE type 630 were also used. Wind screens, 12 in. in diameter, of approximately hemispherical design, and covered with a double thickness of cheese-cloth, were provided. The pattern has become reasonably conventional, and they are entirely satisfactory in the field, although it is probable that a more detailed study would be profitable. A selective feature of the amplifiers also tended to minimize wind noise, and no trouble was encountered from that source. Satisfactory protection against moisture and moderate rains was provided for the 633-A microphone by covering it with an extremely thin membrane. The product sold by the Young Rubber Company under the trade name Naturalamb was the most satisfactory of those tested.

Receiving Amplifiers for Single-Frequency Measurements. Early measurements were made using sound-level meters and cathode-ray oscilloscopes. The selective amplifiers used later were designed particularly to reduce the effect of the complex wave form from the siren source but were found very helpful generally in reducing external noise from wind, airplanes, motor vehicles, etc. A resistance-capacitance network of the type known as Bridged-T was used in the negative-feedback path of a high-gain amplification stage to reduce the gain for all frequencies except one. The theory of the circuit has been discussed by Scott[34] and that of the Bridged-T network by its inventor, H. W. Augustadt,[35] and by Tuttle.[36] The network has been shown to operate in a manner similar to the familiar Wien bridge.

Phase Measuring Systems. Several methods of phase measurement were used.

1. Lissajous Figures. Perhaps the best known of all phase measuring systems is the use of the ellipse pattern produced by placing the sine wave signals directly on the horizontal and vertical amplifiers of the oscilloscope. While accurate quantitative measurement over a considerable range of phase difference is difficult, the method is valuable as an accurate way of adjusting the amplifiers for equal phase on a test signal, for comparing the frequencies of the two oscillators, and for rapid qualitative observation of phenomena. The earlier studies were made with this method with the addition of a calibrated, manually operated phase shifter. The phase was adjusted by hand to zero, as shown on the oscilloscope, and the phase shifter reading was recorded. Observations made in this manner were necessarily slow and could be used only when the atmosphere was quiet, or at low frequencies and short distances.

2. Step-Pattern Method. The first method of instantaneously recording phase was based on the addition of two square waves. The combined wave was placed on the vertical amplifier of the oscilloscope, with the conventional linear sweep on the horizontal plates. The traces were photographed by a motion picture camera. Considerable difficulty was experienced in using this method in the field because instability of both the sound-source frequency and the gasoline-driven power supply unit made synchronizing the oscilloscope sweep very troublesome.

3. Broken-Circle Method. In the step-pattern method an ambiguity in phase of 180 degrees occurred unless considerable extra equipment was added. The broken-circle method was developed to overcome this disadvantage. As shown in the block schematic (Figure 29) the 90-degree phase shifter (the variable phase

control in Selective Amplifier I) was used to form a circle on the oscilloscope screen from one of the signal inputs. A fixed step pattern was formed from the second signal input by the phase shift control of Selective Amplifier II.

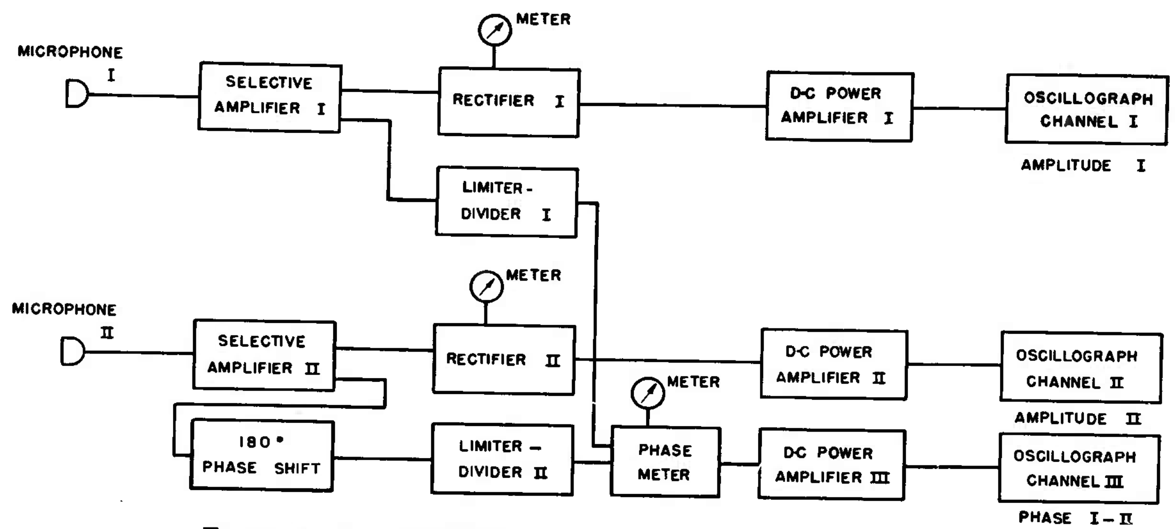


FIGURE 28. Direct recording of phase and amplitude. Block schematic.

The step pattern was impressed on the control grid, or so-called z axis of the oscilloscope cathode-ray tube, blocking out a portion of the circle corresponding to the negative signal peak, and leaving a bright spot at the positive peak.

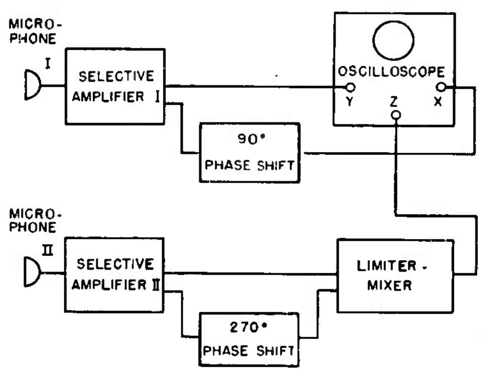


FIGURE 29. Broken-circle phase measurement.

The width of this blocked-out portion could be controlled by adjusting the phase network in Selective Amplifier II. The phase could be read directly from the screen by a common protractor, and the amplitude at Microphone I could be read from the radius of the circle. Photographs obtained by this method are shown in Figure 30.

4. Final Method. The method of phase measurement finally adopted, because it was found most satisfactory in application to direct electromechanical recording, was one based on a circuit developed by the Sperry Gyroscope Company which was made available for this work through the courtesy of that organization. This method employed the familiar Eccles-Jordan trigger circuit and comprised diode limiters and the phase meter proper, as shown in the block schematic (Figure 28).

In common with several other methods of phase measurement, the system chosen began by converting the incoming signals into square waves of constant amplitude. It was essential to maintain the symmetry of the sine wave form, keeping the zero intercepts at their original points. The advantages of a symmetrical type of limiter, such as the biased diode arrangement, were apparent. The basic principle was that of shunting the circuit with two diodes in opposite directions, so biased that they conducted as soon as the biasing voltage was exceeded, effectively chopping off the peak of each wave. By amplifying the chopped wave and chopping again in a similar manner, a wave which was virtually square and of constant amplitude was obtained.

The trigger circuit of Eccles and Jordan has become an important component in many recent schemes. It consists of two vacuum tubes so interconnected that the voltage on the plate of each controls the grid voltage of the other in such a way that plate current flow in one biases the other to cutoff. Thus, at all times, one and only one of the tubes is conducting. The action is shifted from one tube to the other by the application of a signal pulse on the grids. In applying this circuit to phase measurement, the sine signal received was converted to a square wave in the manner previously discussed, and was passed through a capacitance-resistance

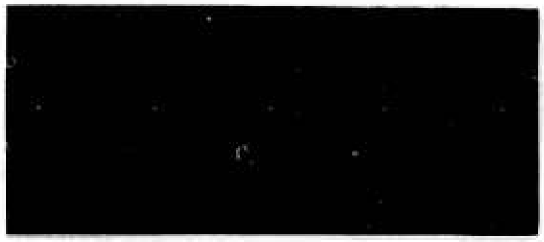


FIGURE 30. Sample record for broken-circle method.

series combination which served as a differentiating network.[37] The resulting sharply peaked waves were applied to the grids of the two tubes comprising the trigger circuit, which was so biased that it responded only to positive pulses of energy. Transfer of conduction from one tube to the other thus occurred for each positive impulse, such as those at a and b under *Differentiated Signals* in Figure 31. If the potential difference between the two plates (or the two cathodes) of the trigger circuit were placed on an oscilloscope screen, the resultant wave form would resemble that of Curve 4 in Figure 31, in which the length d of one side of the rectangular pulse followed the proportionality $\Delta\phi/360 = d/\lambda$ through the entire 360 degrees. If the wave were applied directly to an ordinary d-c meter, it would read an average value shown by the dashed line in the drawing, because of the inability of the needle to follow the rapid changes. This d-c reading would be directly proportional to the length of the rectangular pulses, and hence to the difference of phase between the incoming signals. As applied to the recorder, it was necessary to include an integrating network of resistors and shunt capacitance to replace the natural ballistic characteristic of the meter movement.

Recording Equipment. As indicated above, the first measurements were manually recorded. Development of the system for photographing oscilloscope traces permitted more rapid measurements, and enabled work at longer distances and higher frequencies. Reduction of the data to usable form, however, required much tedious work and could not be done until the films had been processed. Extension of the project to include photographing a number of meteorological observations simultaneously was contemplated but was abandoned in favor of the direct-recording method.

A thirteen-channel recorder (see Figure 32) was designed and built by the Rahm Instrument Company in accordance with requirements. Each coil is supported by a beryllium-copper, spider-shaped spring suspension, and is linked through a simple lever system to a pointer 5 in. long, made of two lengths of fine aluminum tubing with a reinforcing structure of horsehair cloth cemented on. The tip is a short loop of Nichrome wire, and a heating current of about 0.8 amp at 1.25 v is passed through it. Recording is on Thermo-Contax paper, which is coated with an easily fusible wax surface; the surface is effectively lubricated by the melted wax, and there is no measurable damping of the pen response from the friction of the paper, as in most ink recorders. The unit is easily capable of traveling over a range from maximum deflection to zero in less than $1/80$ second. A peak-to-peak deflection of about 2 in. is available, with some departure from linearity at the extremes. It was generally limited to 1 in. for improved linearity. The thirteen units are mounted in two rows and are just 2 in. wide so that, allowing 1 in. to each pen, the 14-in. paper is covered efficiently.

Truck. The recorder, phase and amplitude measuring circuits, meteorological instrument circuits, the Webster-Rauland power amplifiers and oscillators, and associated test and control equipment were all mounted on standard panel

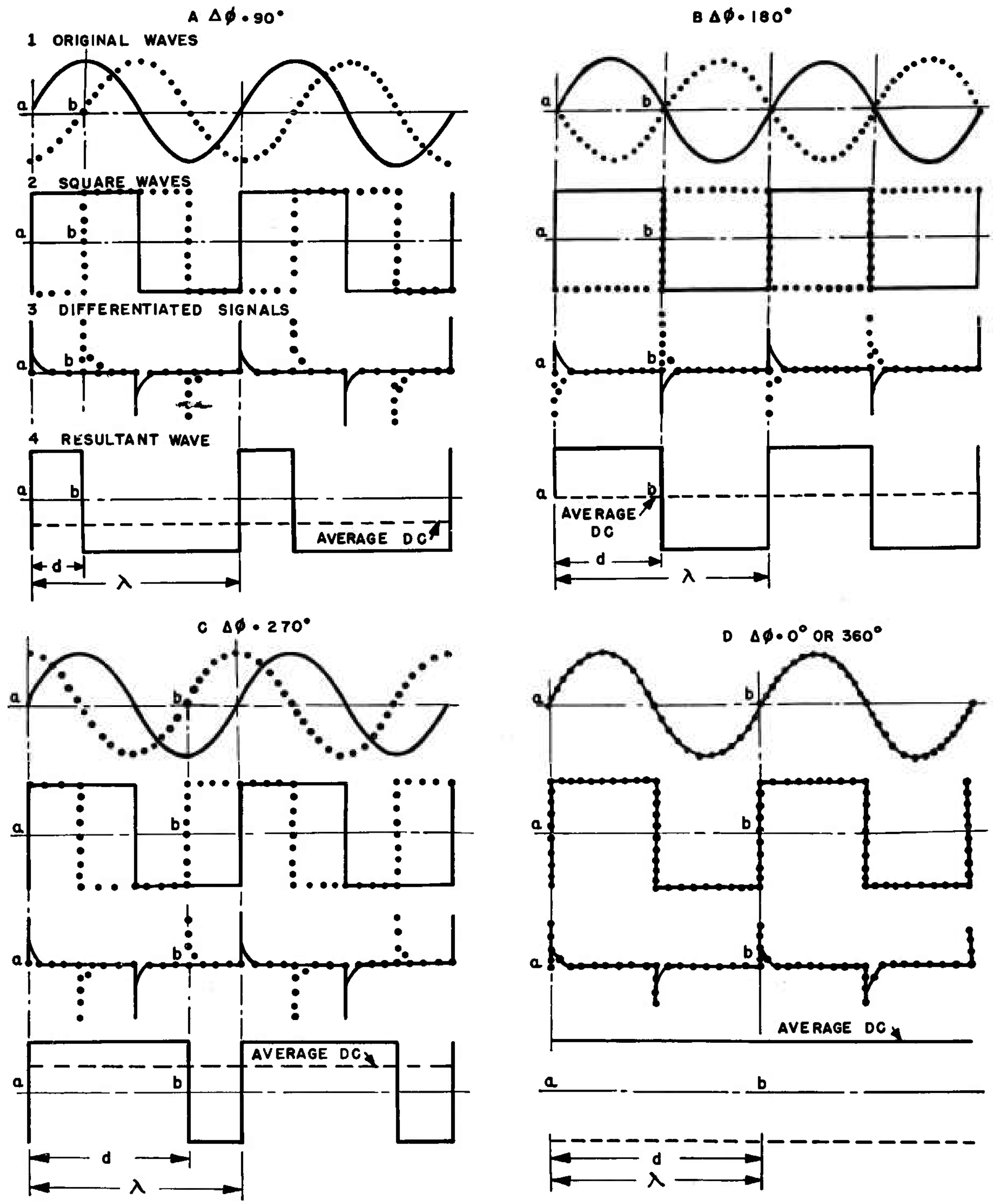


FIGURE 31. Trigger circuit—phase measurement system.

racks in a Ford 1.5-ton panel truck. A set of six reels with hand cranks was installed in the rear of the truck to accommodate the microphone cables and field wire leads to the sound source and meteorological instruments.

Power Supplies. The source of primary power in the field was a Universal gasoline-driven generator, Model 1500-B. This unit, which weighed 410 lb, was rated at 1,500 w, 110-120 v at 60 c, and was mounted on rubber shock-absorbing mounts in a standard 4x7 ft Army trailer. The trailer was large enough to accommodate, in addition, the loud-speaker referred to above as the 5-ft horn. The Ford truck and trailer thus provided a complete, independent system for field measurements.

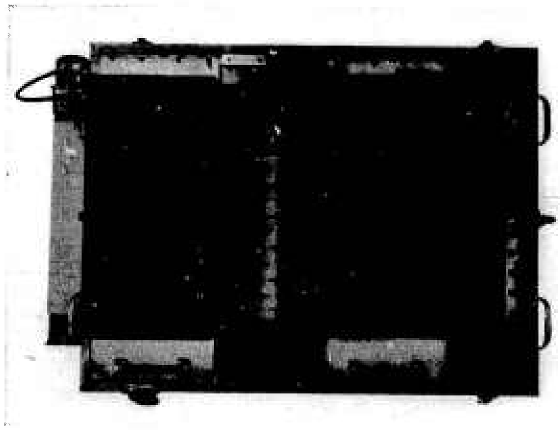


FIGURE 32. Rahm recorder.

Mast and Associated Equipment. Some of the measurements were made as a function of the height of the microphones above the ground. A 50-ft molded plywood radio antenna mast was secured for this purpose on loan from the U. S. Army. It is shown in Figure 33, representing a typical setup during studies at Fort Bragg. The sound source—in this case the large stereophonic horn mounted on an Army truck—is shown 400 yd distant at *A*. The movable microphone is located in the wind screen at *B*, guided by two tightly stretched wires passing through tubes on the sides of the wind screen, and pulled by a third wire which runs through pulleys at the top and bottom of the mast. The equipment shown on the other side of the mast at *D* and the drum *G* were used in the meteorological studies and will be described subsequently. The reference microphone in its wind screen is discernible on the ground at *C*, and a third microphone, used in other tests, may be observed immediately below the wind direction indicator *E*.

Interpretation of the phase records required a high degree of accuracy in the position of the moving microphone. Even with the guide wires, which greatly reduced swaying and swinging of the microphone, it was found desirable to station an observer with a surveying transit at a point about 200 ft from the mast (not shown in Figure 33) in a direction perpendicular to that of the sound path.

In some of the tests a second similar mast was used at some point between the sound source and the receiver.

Impulse Measurements

Impulse measurements were made using both the Army GR-3-C system and the Dodar system. In some cases modifications of the system were introduced. The systems are outlined in Figures 34 and 35.

Sound Sources. As sources of impulse sounds, only those methods were considered which would duplicate, or at least approach, the acoustic wave emitted by gunfire or an exploding shell. Guns and charges of TNT were used mainly for this part of the investigation. Most of the long-base work involving the GR-3-C recorder was done with guns of various calibers, as was also a good portion of the Dodar tests. Records were made on both muzzle waves and shell-burst waves. For extremely short ranges (100-200 yd) an acetylene gun was used.

Microphones. The only microphones used in the measurements on impulse sounds were the standard U. S. Army T-21-B sound-ranging microphones and the T-21-B modified microphones.

Recording Equipment. The GR-3-C oscillograph and the Dodar have already been described. As a means of studying the amplitude-time difference relationship with Dodar, a device was developed for measuring the amplitude of the sound wave simultaneously with the measurement of its arrival time by Dodar. The amplitude of the first pressure peak was chosen

as the first quantity to be measured, since there was no evidence to indicate that any other point on the wave was more important to the desired correlation. The peak-reading vacuum tube voltmeter which was developed has two channels for reading each of two Dodar inputs. For indicating purposes, it uses two meters (0-1 ma), which, with calibration charts, permit determination of the peak values in terms of db above or below 2.45 peak volts. With a combination of the peak-reading voltmeter just described and the Dodar, it was possible to make a series of measurements at intervals as short as ½ minute.

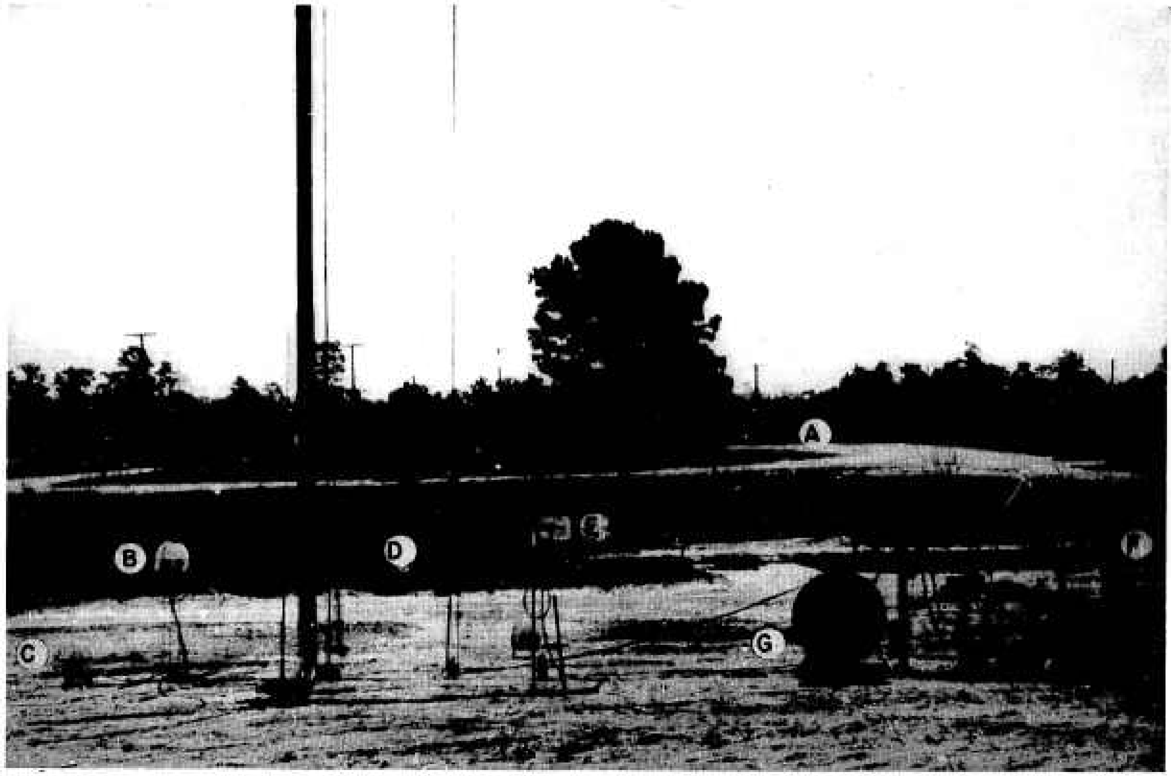


FIGURE 33. Typical field setup.

Meteorological Measurements

An important part of the work was the study of instantaneous micrometeorological conditions at the time of sound recording. Instruments were developed to record wind speed, wind direction, and temperature with a response time comparable with the fluctuations encountered in the transmitted sound. The additional channels of the recording oscillograph were provided to place these factors on the record also as functions of time, and in such a position that their relationships to the received sound amplitude and phase might be observed.

The linear dimensions of any practical meteorological instrument are considerably smaller than those of the wave front distortions called corrugations or serrations and the difference between macro- and micrometeorological equipment resolves itself, therefore, into the time rate of response of the device. Macrometeorological instruments, being intended for measurements of long-period phenomena, are so designed that they average out the rapid fluctuations which are more properly in the domain of micrometeorological measurements. In mechanical instruments this is accomplished by large mechanical inertia, and in thermal instruments by long constants.

The short time constants required of micro-

meteorological instruments implies small masses for the mechanical instruments and low heat capacities for thermal ones; therefore, it was expected that the size of these units would be small and not very rugged. On the other hand, the macrometeorological instruments with large time constants may easily be built with very rugged construction.

Mounts for the meteorological units must satisfy the primary purposes of supporting and

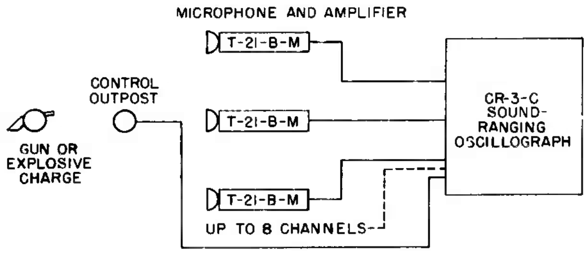


FIGURE 34. Block schematic of oscillographic method—impulse sounds.

protecting the elements, but must not interfere with the ability of the instruments to measure the characteristic desired in free air. Thus, anemometer mounts must be so constructed that they will not affect the action of the wind on the sensitive element. Thermometer mounts must not increase the heat capacity of the unit to the point where its thermal lag is too great to make it usable, and must shield the unit from any direct or indirect radiation without interfering with the free contact of element and air.

The following sections, which describe the instruments actually used, have been separated into those dealing with temperature measurements and those dealing with wind measurements. It will be noted that the thermocouples were used for temperature measurements only, whereas the wire-resistance and thermistor units were used for both temperature and wind instruments. The difference between the use of a resistance-varying element as a thermometer and as an anemometer is merely one of the temperature to which it is heated by the current being passed through it, the former using extremely low values of current and the latter fairly high values.

Measurement of Temperature and its Fluctuation with Time. Three thermal methods were developed and tested for the measurement of temperature:

1. Wire resistance units made of 0.006-in. platinum wire. Their use was finally abandoned because of their short time constant, which introduced unnecessary complications into the temperature record.

2. Thermistor units, using Western Electric thermistor units.

3. Thermocouples, employing copper and constantan.

Auxiliary equipment was necessary to shield these various instruments from direct radiation from the sun and also from any reradiation by surrounding objects. At night the shields were used to prevent radiation to a clear open sky. The approach to the problem consisted of measuring temperatures at several positions beneath the various types of shades under conditions of bright sunlight and light wind. Each type of shade developed was chosen in an attempt to improve the previous model. An analysis of the results revealed the following: (1) metallic aluminum shading units provided more effective shielding than the corresponding ones of Bristol board coated with aluminum paint; (2) conical shades, with the apex of the cone pointing toward the ground, gave more shielding than with the apex pointing upward; (3) the smaller conical units performed equally as well as the larger ones; (4) disk units above and below the element gave the maximum shielding.

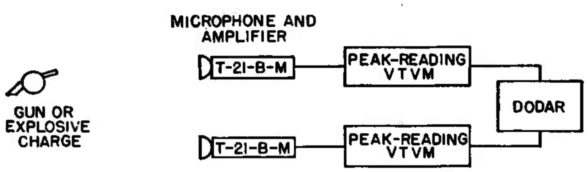


FIGURE 35. Block schematic of Dodar system—impulse sounds.

Measurement of Wind Speed and Direction. The problems involved in wind measurements are somewhat more complicated because wind velocity is a vector in three-dimensional space, whereas temperature is a scalar quantity. This required the use of several channels on the direct-writing recorder in order to determine

wind velocity completely. Two methods were considered: (1) to record the three components of velocity on three separate channels, and (2) to record the magnitude of wind speed without regard to direction on one channel, together with one or two additional channels to indicate direction. In much of the work it was assumed that the vertical component could be disregarded. Limitations of equipment and available channels constituted the main reasons for ignoring the vertical component.

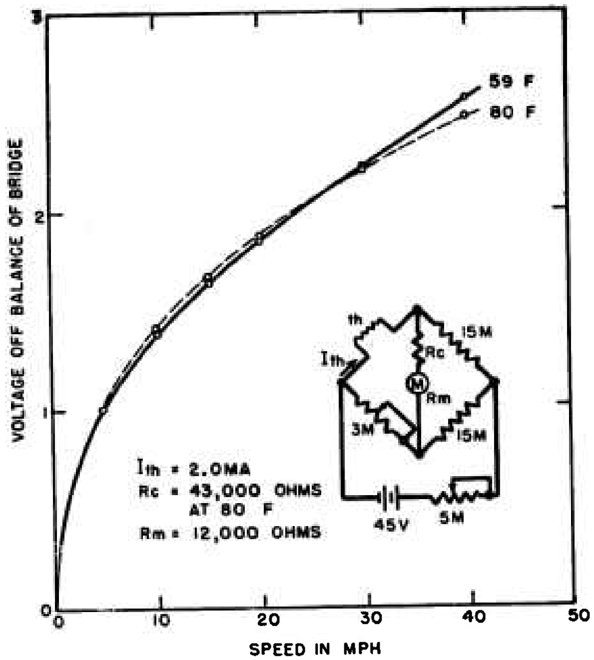


FIGURE 36. Calibration curve for temperature-compensated thermistor anemometer.

Instruments used to measure wind fall into two major classes: (1) mechanical and electromechanical systems and (2) devices in which an electrical parameter, such as the resistance of a heated wire or similar element, is made to vary directly with the wind.

Five types of instrumentation were developed for the measurement of wind velocities, and some work was expended on the development of calibrating systems.

1. *Wire resistance anemometers* of fine platinum wire, heated from 300 C to 1,000 C above ambient still-air temperature. This type of instrument was used in a number of field tests, but it presented some difficulties. It is possible that with a careful study of different types of hot wires, operating temperatures, and varying frequency characteristics in the amplifier, a satisfactory instrument to measure very rapid fluctuations might be developed.

2. *Thermistor anemometers*. These units were similar to those used to measure temperature, but were operated heated. Fairly successful attempts were made to compensate for ambient temperature changes and to obtain a response linearly proportional to wind speed. Figure 36 shows the degree of correction achieved with a circuit using for R_c a Keystone Carbon Company type LE NTC resistor, which possesses a negative temperature coefficient.

3. *Cup anemometers*. Conventional rotating-cup anemometers were used in some of the studies. They were found sensitive to wind speeds of 2 or 3 mph, but could not be relied on for short-period gusts or changes in the wind. Consideration was given to designing a mechanical anemometer of a more miniature type, but the problem of introducing critical damping without losing quickness of response remained unsolved.

4. *Wind direction indicators*. A conventional wind vane carrying a pointer and calibrated scale was used in all the early studies. A very simple device for application to direct recording was made, using a vane of aluminum sheet, 9x12 in., mounted by means of a counterweighted dowel rod on a ball-bearing-supported rotor, which in turn rotated a brush on a potentiometer. Ordinary 0.5-watt, 20,000-ohm composition resistors were connected between the segments to form the potentiometer. With a 22.5-v battery connected across the terminals, the output was more than enough to produce full-scale deflection on the Rahm recorder through the regular driver amplifier. The resulting plot in the recorder increased steadily in 12-degree steps with the angle of rotation. This vane was used in many of the field tests and may be seen at E in Figure 33. This wind vane was sufficiently sensitive to respond to a steady breeze of 1 or 2 mph, but was relatively slow in response and would not follow short-period gusts of air.

A system using selsyn motors and a torque amplifier was developed which presented very little inertia and would respond to small currents and rapid changes of the order of 0.5 second with very little tendency to oscillate or overshoot. The basis of the instrument was a small selsyn unit designed for airplane-metering applications and sold as Telegon, Type 315-F-9013. Some mechanical difficulties were encountered in developing a satisfactory 360-degree continuously rotatable potentiometer with low contact resistance and low frictional losses, and the project was not satisfactorily completed. An adequate answer might lie in the commutator type of potentiometer described in the direct systems.

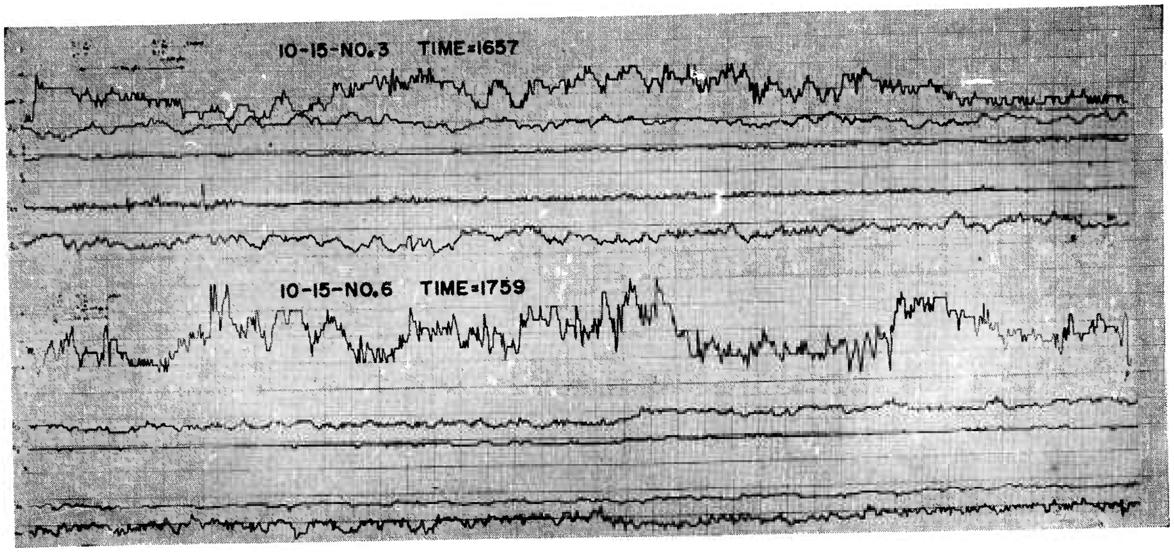


FIGURE 37. Phase difference, acoustic amplitude, and wind curves at distances of 200 and 800 yd.

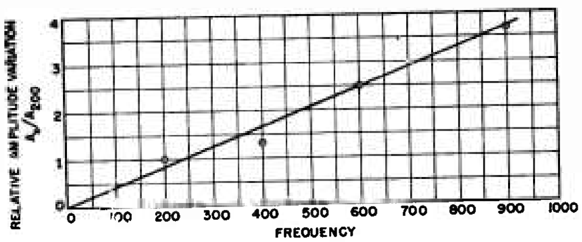


FIGURE 38. Dependence of amplitude fluctuations on frequency.

5. *Velocity component meters.* For the study of certain relationships, it may be more convenient to record directly the magnitude of each component of wind velocity, rather than the speed and direction of the wind. Several devices were built, and others considered, to measure these components by measuring the drag forces exerted on a plate, sphere, or other solid, but a completely satisfactory instrument was not built in the time available.

Calibrating Systems. Calibration of anemometric instruments requires either a stream of air of known speed, or a means of moving the instrument with a known velocity through relatively quiet air. Systems of the first type, exemplified by a small wind tunnel, and of the second type, exemplified by torsion pendulum and rotating arm systems, were employed.

General Comments. The development of micrometeorological instruments deserves further attention. It was felt by the Division that its work in that direction resulted in some contributions and suggestions which should prove of value in the future. One further suggestion which should be mentioned is the desirability of developing means of measuring quantitatively the acoustic parameters of a given terrain; it has only recently become apparent that a study of terrain (though not generally regarded as a meteorological factor) is highly important.

5.5.4 Experimental Results

Effectiveness of the Standard Meteorological Correction. In determining the azimuth of a sound source by means of a pair of microphones, application of the standard meteorological correction statistically improves the results. Since the effectiveness of the standard method varied considerably at different times, the following two suggestions are made. (1) Whenever possible, use the average of several locations of a sound source, rather than a single determination. (2) When meteorological conditions are changing, obtain meteorological messages frequently, rather than at regular prescribed intervals, usually of several hours' length.

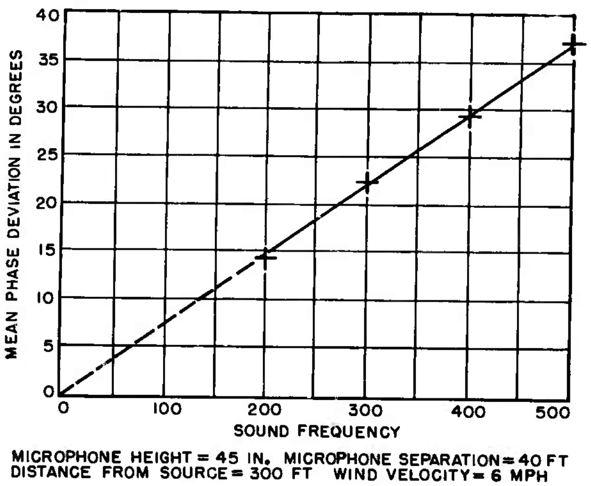


FIGURE 39. Acoustic frequency dependence on phase fluctuations.

The determination of the effective wind is open to the serious objection that the averaging of the weighted winds does not treat them correctly as vectors. In addition, the whole method of weighting is empirical and can be expected to be satisfactory only on the average. Therefore, it is suggested that the effective wind should be determined by plotting the weighted minute winds as vector quantities in a manner similar to the plotting of the ballistic wind for artillery purposes.

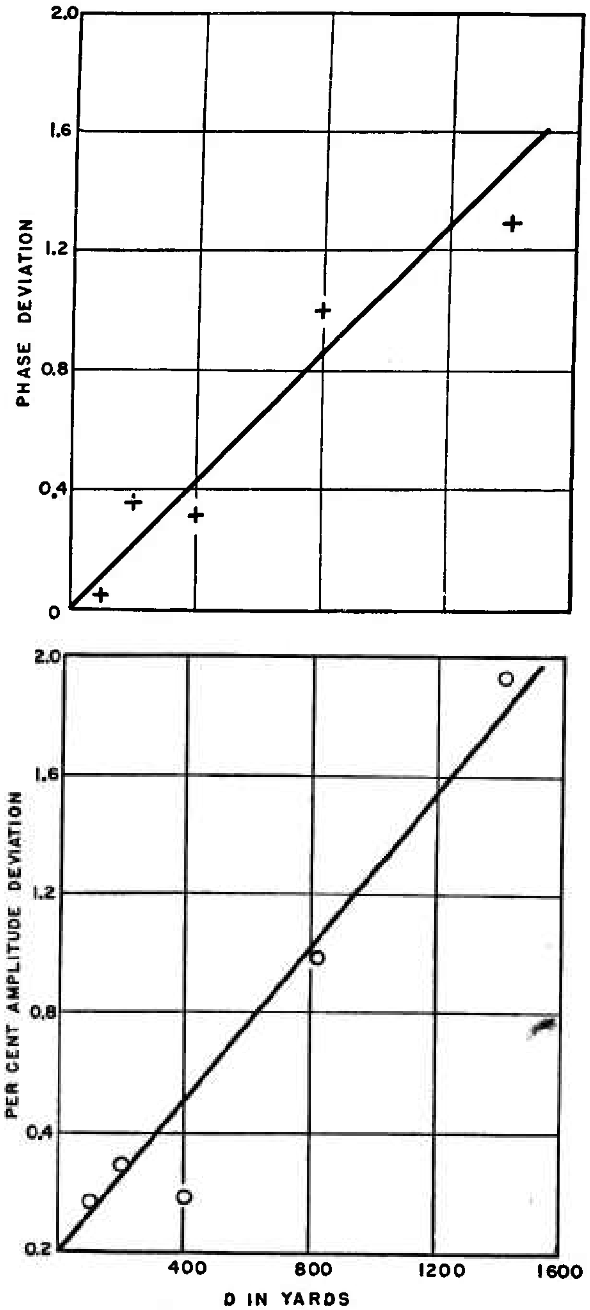


FIGURE 40. (*Top*) Variation of phase deviation with distance. (*Bottom*) Variation of per cent amplitude deviation with distance.

The determination of the effective temperature is subject to criticism on several counts. One is that the choice of the temperature at 500 ft seems rather arbitrary. Another difficulty is the assumption that the temperature at 500 ft is 2 F less than that at the ground. This certainly is not the case when there is a temperature inversion.

Early Experiments on Micrometeorological Fluctuations. In the earlier experiments employing one or more pairs of microphones, the two microphones of a pair being equidistant from the source, and a steady sound source of a given frequency, the following general characteristics were usually found:

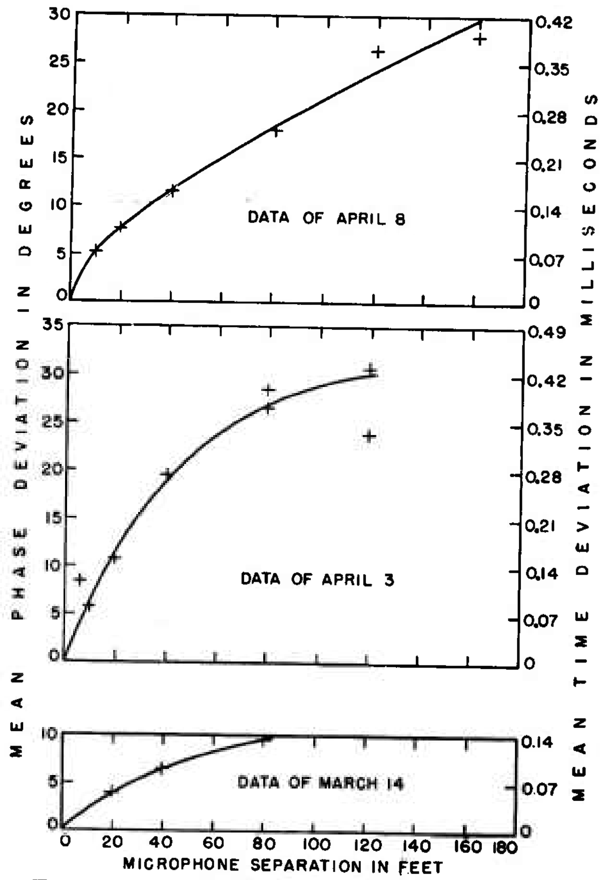


FIGURE 41. Phase deviation as a function of microphone separation for perpendicular arrays.

1. Rather large fluctuations in phase difference, of an order corresponding to fluctuations of 1 millisecond with a microphone separation of 40 ft;

2. Rather rapid fluctuations in phase difference, a complete cycle of this fluctuation frequently occurring in a 20-second period;

3. A mean phase difference not equal to zero;

4. Rapid, large changes in wind speed and direction;

5. No obvious correlation between instantaneous values of phase difference and wind speed and direction.

Magnitude of Micrometeorological Fluctuations. The difference in the times of arrival of a sound impulse from a given source may vary rapidly with time. Guns, mortars, shell bursts, and TNT were used as sources and the GR-3-C and Dodar as recorders and indicators. The standard deviation of the time interval errors for a group of shots showed values ranging from 1.5 milliseconds to more than 30 milliseconds, the smaller values being obtained at the shorter ranges and smaller microphone separations. As a result of this it is concluded that deviations in the difference of arrival times due to rapidly changing conditions may be a serious source of error in sound ranging and that further effort to reduce this source of error is justified.

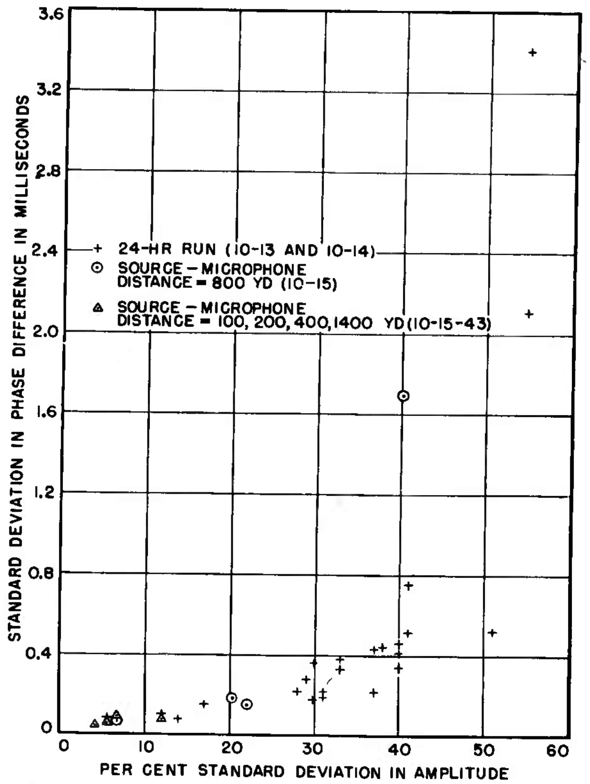


FIGURE 42. Standard deviation in phase difference as a function of per cent standard deviation in amplitude.

Relationships for Steady, Single-Frequency

Sources. In an effort to investigate further the short-period fluctuations referred to above, experiments with a steady sound source of a given frequency were performed, and the relationships between the amplitude of the wave and the time of arrival under varying conditions were studied (see Figure 37,[10a] obtained by reading amplitudes and phase difference for two microphones every ⅓ second). It was found that the magnitude of the amplitude fluctuations at one microphone is roughly proportional to the frequency of the sound (Figure 38) and that the magnitude of the fluctuations in the phase difference for two microphones increases approximately linearly with the frequency (Figure 39). It was concluded, therefore, that the mean time deviation is independent of the frequency of the sound.

The magnitudes of the fluctuations in both amplitude and phase difference increase with the distance from the source. For the phase difference, the relationship is roughly linear, with possibly a leveling-off tendency at large distances as obtained from data in Figures 37 and 40.

The magnitude of the fluctuations in phase difference increases with the microphone separation, but this increase is not linear (except when the microphones and source are in line), and there appears to be a leveling-off tendency at the larger separations (Figure 41). Since the mean difference in arrival times for a pair of microphones increases linearly with their separation, it follows that (1) the mean azimuth error due to this effect decreases with increasing microphone separation, and (2) short-period meteorological fluctuations are a more serious source of error in sound ranging when the microphone separation is small, as for the Dodar sub-base, than when the separation is large, as in the case of a 2- to 4-sound-second sub-base.

The magnitudes of the fluctuations in both amplitude and phase difference are greater in the daytime than at night.

The magnitudes of the amplitude and phase fluctuations are greatest on gusty days, or days of atmospheric turbulence, but no quantitative data sufficient to establish exact relationships were obtained.

When the magnitude of the fluctuations in amplitude is great, the magnitude of the fluctuations in phase is also great. More specifically, for small amplitude variations the time difference variation is approximately proportional to the per cent amplitude variation, but for greater fluctuations the time difference variation is a rapidly increasing function of the per cent amplitude variation (Figure 42). Consequently, the seriousness of errors in sound ranging due to short-period meteorological fluctuations increases rapidly with the degree of turbulence, and current sound-ranging methods become ineffective when turbulence is excessive.

The magnitude of the fluctuations in phase difference is large when the amplitude of the received sound is low, and vice versa. This low sound intensity emphasizes the difficulties of sound ranging in a highly turbulent atmosphere.

It is highly probable that there is a correlation between the variations of the amplitudes of the sound received at two microphones and the variations of the phase difference between the two microphones (see Table 4 for typical data). This correlation may be stated as follows: that portion of a wave front arriving earlier than the average usually has an intensity below the average, whereas a portion arriving later than the average usually has an intensity above the average; that is, the correlation coefficient between phase and amplitude is usually negative. Although the long-time correlation coefficient is usually negative, it was observed that for short periods of time it may reverse itself and become positive. However, the periods of reversal, during which there is no correlation, are relatively short and infrequent. Typical results are shown in Figure 43, which refers to points taken off a continuous record (Rahm recorder) at intervals of 1.36 sec; in this particular series of readings, a single microphone was placed 50 ft above the ground at a distance of about 200 yd from the horn, and the phase of the microphone measured relative to that of the source. Such a correlation alone would not suffice to improve sound ranging greatly, but combined with some other factor or measurement which would show the sign of the correla-

tion, it might result in considerable improvement.

The possibility of correlating the sign of the phase-amplitude correlation coefficient with one or more micrometeorological factors should be investigated. Much of the necessary equipment for such an investigation was developed, but time did not permit field tests with it.

Should such an investigation prove successful in correlating the sign of the phase-amplitude correlation coefficient with measurable micrometeorological factors, the possibility will exist of applying the phase-amplitude correlation to correct those time difference errors in sound ranging which are due to short-period meteorological fluctuations.

There is some indication that the phase-amplitude correlation is good when no temperature inversion exists, wind speeds are high, and the air turbulent, and that the correlation is poor when a temperature inversion exists, wind speeds are low, and there is little turbulence. Such an indication suggests the possibility of applying the correlation when it is most needed, namely, when sound-ranging conditions are poor, and the errors due to the micromet are large.

Relationships for Impulse Sources. Similar measurements were made using sources of sound impulses and both long and short bases. The results obtained were completely consistent with those obtained with single-frequency sources. Two examples follow.

1. For impulse sounds the standard deviation of the error in the arrival time interval for two microphones increases with the distance of the source.

2. For impulse sounds the error in the arrival time interval for two microphones and the amplitude ratio in decibels for the same pair of microphones show a considerable degree of correlation. The sign of this correlation is usually, but not always, negative. (See Figure 44,[10b] which is typical of the results obtained.) There is also some indication that this correlation is greatest when meteorological conditions are not favorable for sound ranging.

Vertical Structure for Steady, Single-Frequency Sources. Experiments were made using single-frequency sources and measuring ampli-

TABLE 4. Phase difference vs amplitude.

Number and time of record	Separation of microphones (ft)	Number of readings in group	Number of groups	Correlation coefficient	Probability of distribution being random
8	20	80	8	—0.519	0.2
1605		40	16	—0.545	0.03
		20	33	—0.358	0.05
		10	66	—0.308	0.01
9	80	80	9	—0.563	0.1
1759		40	18	—0.674	0.002
		20	36	—0.448	0.005
		10	72	—0.327	0.005
10	20	80	8	—0.289	0.5
1312		40	16	—0.309	0.2
		20	33	—0.447	0.01
		10	66	—0.491	<0.001
10	160	80	8	—0.760	0.03
1812		40	16	—0.513	0.04
		20	33	—0.557	0.001
		10	66	—0.506	<0.001
20	80	80	10	+0.261	0.5
0410		40	20	+0.268	0.3
		20	40	—0.057	0.7
		10	80	—0.130	0.3
23	160	80	10	—0.036	0.9
0755		40	20	—0.175	0.5
		20	40	—0.144	0.3

tude and phase as a function of the height above the ground. Typical results are shown in Figures 45 and 46.

Above dry, plowed ground a minimum in amplitude of the sound occurs, not at the ground, but at a height which is roughly proportional to the wavelength (between 5 and 10 ft for 200 c), whereas the phase, corrected for varying distance to source, increases with height (see Figures 45 and 47). These amplitude and phase characteristics are independent of the existing temperature gradient.

Above water-soaked ground the amplitude and phase structure is dependent on the temperature gradient as well as the frequency. Below 400 c there is no pronounced amplitude minimum above the ground (Figure 46).

Above very wet, but not water-soaked, ground both the meteorology and the terrain are controlling factors.

The above results may be summarized as follows: the vertical amplitude and phase structure above water-soaked ground (acoustic impedance high) is determined predominantly by the temperature and wind structure, whereas above dry ground (acoustic impedance low) the terrain is the predominant factor. In intermediate cases, when the ground is wet but not water-

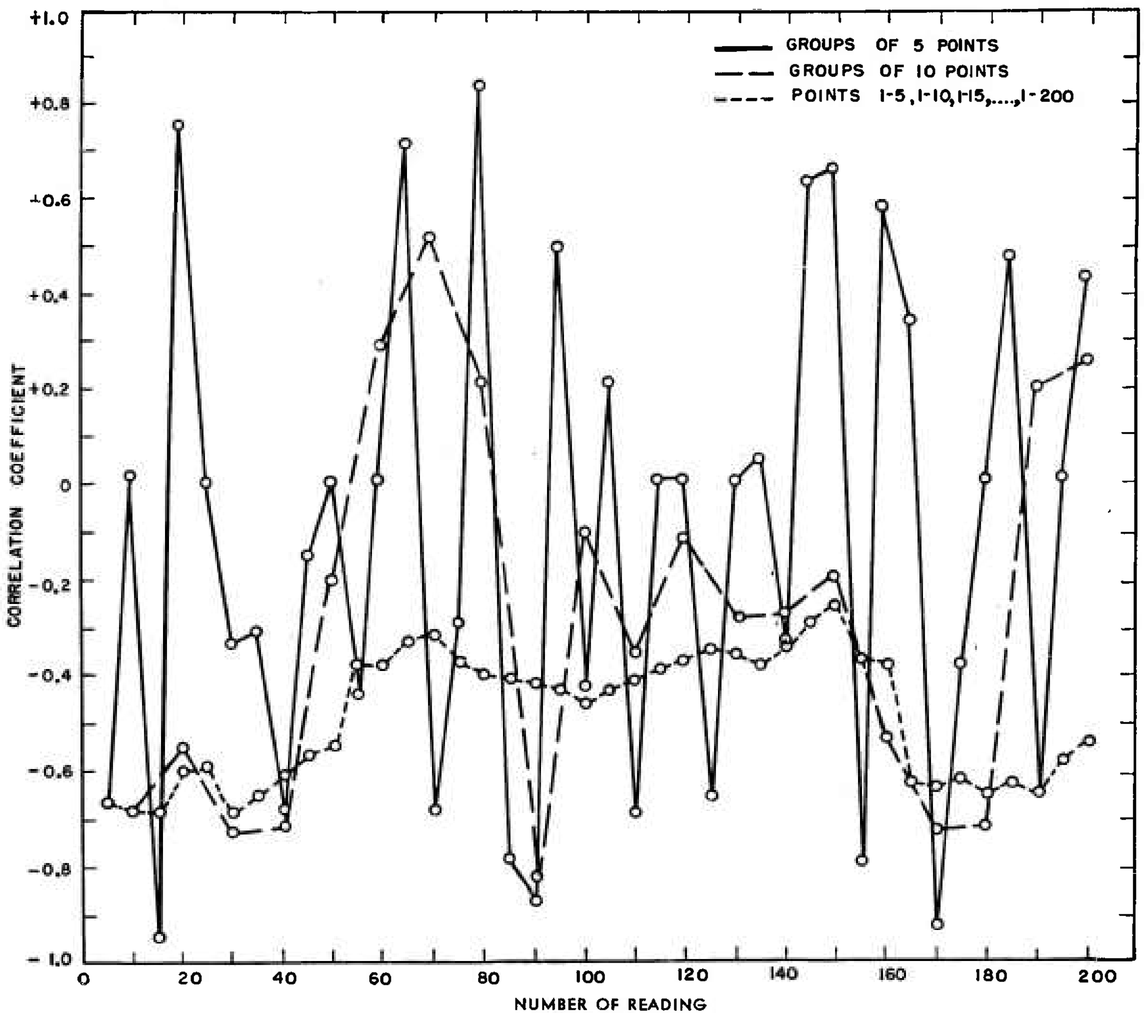


FIGURE 43. Correlation coefficients for phase vs amplitude.

soaked, both meteorological factors and terrain affect the amplitude and phase structure.

The importance of terrain as a factor affecting sound propagation increases as the acoustic impedance of the ground decreases. (Acoustic impedance of the ground, in general, is decreased by increased porosity, as when the ground dries out, and by growth of grass or other vegetation.)

There are indications that under certain conditions sound ranging may be improved considerably by elevating the microphones well above the ground.

5.5.5 Theoretical Work

The preceding sections have dealt mainly with the description of apparatus and methods of measurement, and with the analysis of data largely from a statistical point of view. In the remaining sections there will be discussed various theoretical problems which served to guide the experimental work and to indicate what types of further investigation might be desirable.

Persistence of a Distortion of a Wave Front. The discussion of this problem was limited to the study of the persistence of a spherically shaped boss or bump on an otherwise plane wave front in a stationary, homogeneous medium.[5]

The specific problem considered is shown in Figure 48. The wave front at time t is denoted by its plane section FPF, with the spherical bump having its center at P. The radius of the sphere is R, and the radius of the circular region in the wave front occupied by the bump is u. The advance of the wave front at P is measured by v. In the computations carried out, R was taken as 20 ft, u as 17.32 ft, and v as 10 ft.

The method used for solving the problem was that developed by Helmholtz in his analytical formulation of Huygen's principle. The velocity potential was computed at a point A on the axis OP (extended) and at a point B on the perpendicular through the axis where $AB = u$.

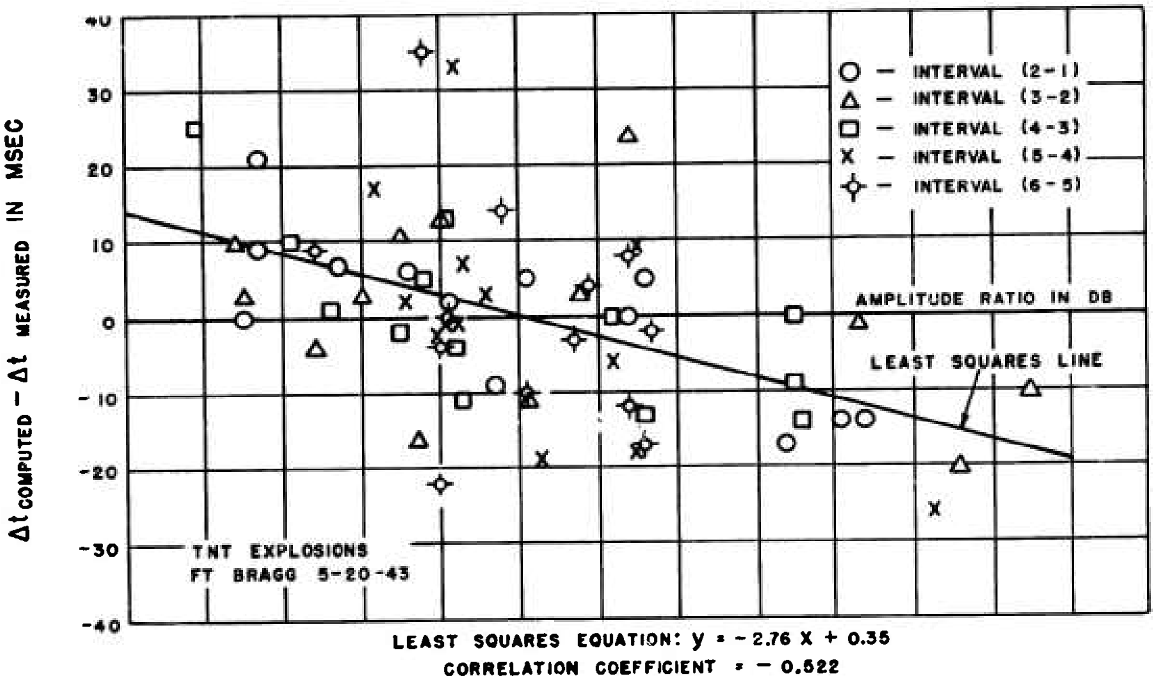


FIGURE 44. Time error vs corrected amplitude ratio.

This was done for different distances x along the axis and for different wavelengths λ of the harmonic sound radiation assumed. For the "on-axis" case (point A) the contributions to the velocity potential due to the plane and spherical wave fronts were computed separately. The fundamental idea used in the "off-axis" case (point B) was to add the contributions at B due to the spherical wave and due to a plane wave over the whole wave front, and then to subtract from that sum the contributions at B due to a plane wave over an area equal to that of the circle cut out by the spherical wave at the original wave front.

The calculations showed that the persistence distance depends on the wavelength. If the arbitrary assumption is made that the bump will be considered to be smoothed out when the difference in times of arrival of the wave front at A and B is less than 0.02 millisecond, then it is found that for a wavelength of 10 ft, the persistence distance is 300 ft; for a wavelength of 50 ft, about 1,000 ft; and for a wavelength of 100 ft, about 500 ft.

The connection between this and the general problem of sound ranging lies in the fact that sufficiently persistent irregularities in the wave front would result in a change in the times of arrival of the wave front at the different microphones of an array, and thereby require for their correction information over the whole sound path and hence into enemy territory. However, if the irregularities are random, short-time effects, they may be correctable by using data obtained in the vicinity of the microphone base line, that is, within our own lines. Therefore, it was considered desirable to concentrate on an experimental study of conditions in the immediate vicinity of the microphones.

The Acoustic Transmission Properties of a Moving Thermal Lamina of Air. Consider a plane wave incident on a sheet or lamina of moving air. Suppose the thickness of the sheet is l (see Figure 49), the temperature of the sheet is $T_1 = T + \Delta T$, where T is the temperature of the surrounding medium in degrees absolute, the static pressure in the sheet is the same as that of the surrounding medium; and,

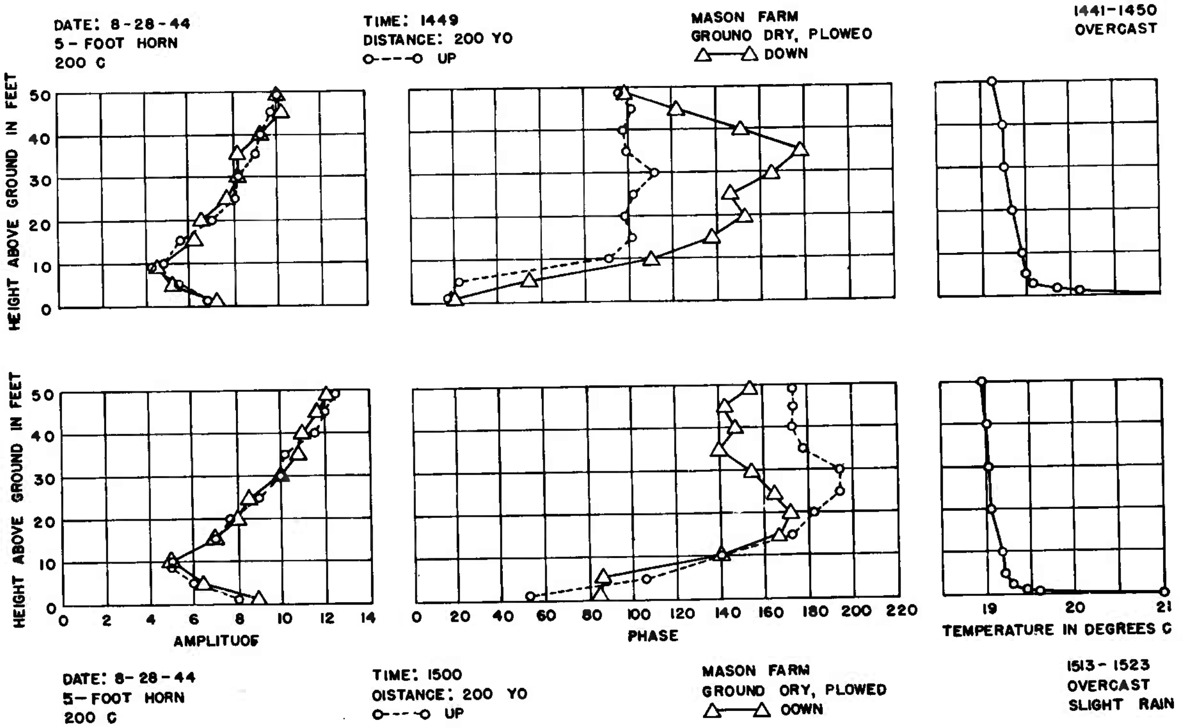


FIGURE 45. Amplitude and phase vs height over dry, plowed ground.

further, suppose the sheet's velocity is V_y parallel to the boundary.

The problem was to determine the acoustic transmission characteristics of this sheet, both as regards the amplitude and the phase of the transmitted wave. This was done for sheets of arbitrary thickness. The discussion, which is largely qualitative, is based on fundamental hydrodynamics.

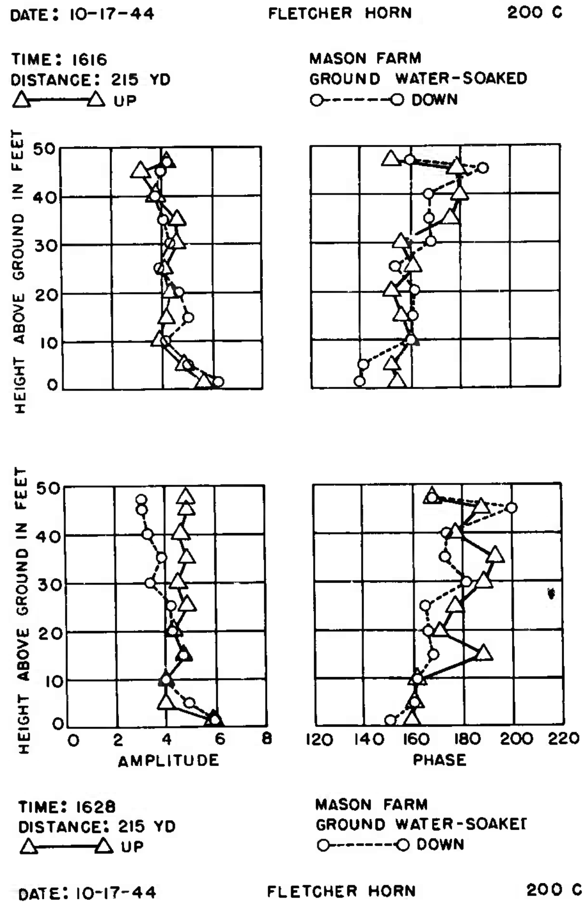


FIGURE 46. Amplitude and phase vs height over water-soaked ground.

This study was undertaken to investigate a possible mechanism to explain the observed phase-amplitude correlations. A plane wave will traverse a warm sheet in a shorter time than if the sheet were cold, and it will traverse a sheet which has a component of velocity in the direction of acoustic propagation in a shorter time than one whose component of motion is opposite to the direction of acoustic propagation; in every case, however, the transmission coefficient will be less than 1, since reflection will always occur at each of the boundaries. Hence, if a sound source is equidistant from two microphones, the microphone leading with respect to phase will have the smaller amplitude when warm pockets of air predominate, and the larger amplitude when more cold pockets are present. The following section gives a quantitative treatment of this phenomenon.

Multiple Lamina. When a sound wave passes through a number of sheets of the type just discussed, the resulting amplitude and phase will obviously depend on their relative orientations, spacing, temperatures, and velocities. It is only for the simplest conditions that a practical solution is possible. The sheets were assumed to be parallel, equally spaced, and identical. Furthermore, it was assumed that the reflected energy from each sheet is very small, and once reflected may be neglected.

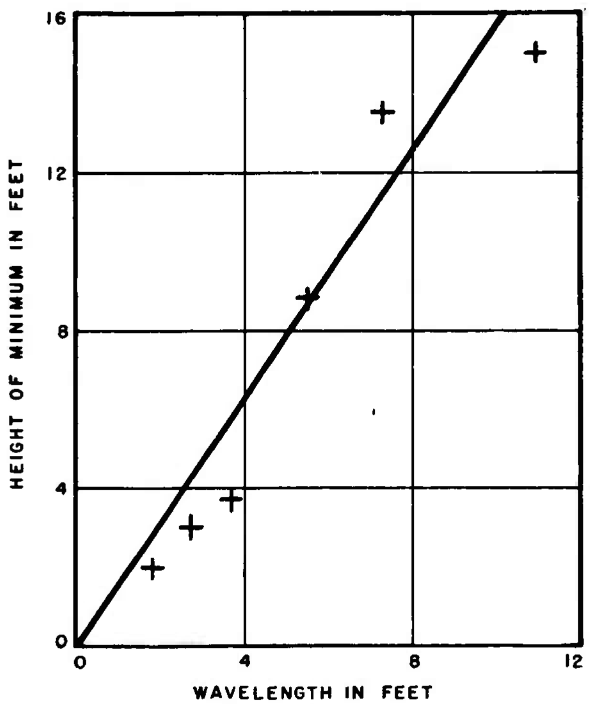


FIGURE 47. Height of minimum in amplitude at various acoustic wavelengths (dry, plowed ground).

Three cases were investigated. First, it was supposed that the difference in phase and amplitude at the two microphones is due to a different number of sheets over each path, the sheets being identical and having the same inclinations with respect to their associated wave normals. Secondly, the case was considered

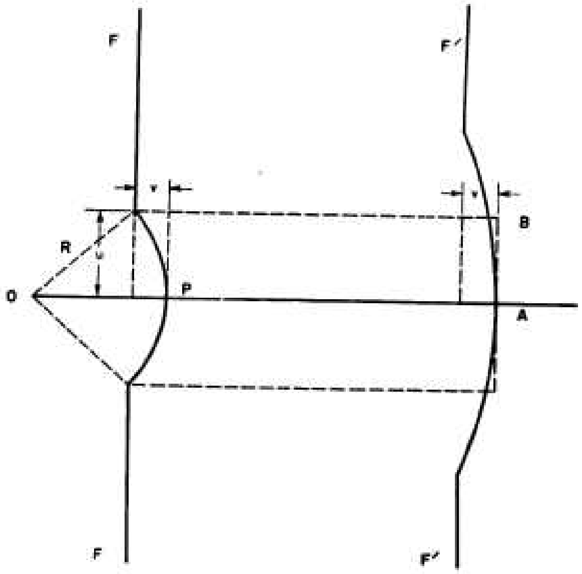


FIGURE 48. Persistence of wave front corrugations.

where the number of sheets over each path is the same, the difference in the two paths being in the angle of inclination of the sheets with respect to the wave normals. Finally, attention was given to the relationships obtained when there is a difference in the thermal or momentum content of the sheets.

The results of the theory did not appear to be of the correct order of magnitude to account for the experimental observations on phase-amplitude correlations; only for angles near grazing incidence could anything like quantitative agreement be found.

Acoustic Phase and Amplitude Relations in a Stationary Medium with a Linear Vertical Sound Velocity Gradient. A stationary atmosphere is generally described as being stratified vertically with respect to the temperature (and consequently sound velocity). The temperature changes are generally gradual, so that no sharp boundaries exist. The most successful treatment of the propagation of sound through such a medium is one which describes the ray paths; the problem here discussed was treated in this fashion. The problem was one of determining the time of travel and the amplitude of a sound ray when the sound velocity gradient is linear and positive, account being taken of attenuation and spreading of the waves from a point source. The ray path considered was one between a source and a receiver, both placed on the ground. Rays reflected from the ground were disregarded.

A stationary atmosphere was considered. It was assumed to have horizontal homogeneity and a vertical temperature gradient obeying the law

$$T = T_0\left(1 + \frac{y}{a}\right)^2, \tag{6}$$

where T is in degrees absolute, and the x and y axes have been chosen so that the x axis is horizontal. Then if c is the velocity of sound

$$c = c_0\left(1 + \frac{y}{a}\right). \tag{7}$$

It is easy to show without mathematical demonstration that the sound rays are circles.

Analysis showed that as the gradient increases (that is, a decreases) both the amplitude and time of travel decrease. Suppose an idealized system of the following type is assumed: (1) two microphones are equidistant from a source; (2) a lack of horizontal homogeneity in the temperature causes the rays to the two microphones to have different values of a; (3) the lack of horizontal homogeneity is such that it does not alter the circular character of the rays. It then follows that the microphone at which the amplitude is least is ahead in phase (smaller time of travel) with respect to the other microphone.

Of interest is the magnitude of the temperature gradient necessary in order that significant time differences be obtained. In order that a difference of 1 millisecond be present between straight-line and curvilinear propagation over a distance of 800 yd, it was found that a must be about 8,000 yd. This corresponds to a temperature gradient of about 1 C in 13 yd. Though

this may be large from a macrometeorological standpoint, it seems possible that gradients of this order and higher may be present near the ground over short periods of time. This is perhaps to be anticipated, since large amplitude changes are to be expected mainly when there is a deviation from a linear velocity gradient, so that focusing of sound rays occurs.

Here again the object was to investigate the phase-amplitude relationship under specified conditions. The results were encouraging, al-

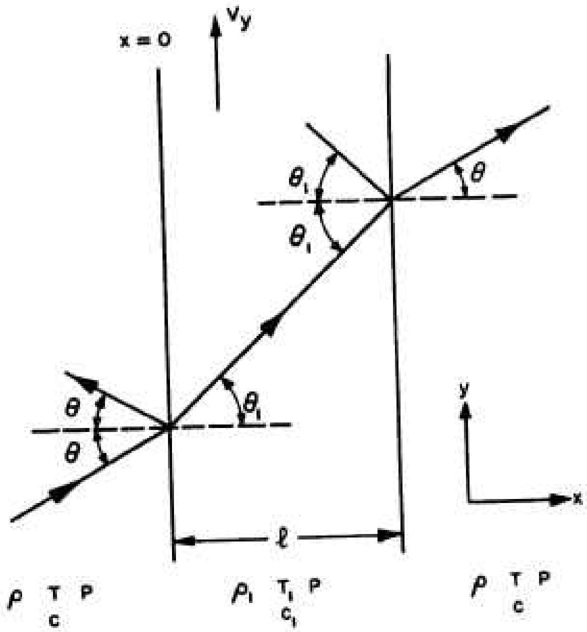


FIGURE 49. Idealized transmission through thermal lamination of air.

though rather extreme conditions had to be postulated in order to obtain results of the order of magnitude of those observed experimentally under uncontrolled conditions.

Phase-Amplitude Relationships in the Interference Field of Two Plane Waves. The problem was to determine the phase and amplitude patterns when two plane waves whose frequencies are the same and whose normals are at an angle with each other interact.

The problem arose from a consideration of the interaction between waves being propagated directly and those arriving at a receiver after being reflected from the ground. Both the magnitude and sign of the phase-amplitude relationship in this situation were shown to be dependent on the locations and spacing of the receivers, and on the frequency of the sound. Thus it was found that the surfaces of equal phase do not coincide with the surfaces of equal intensity.

Sound Propagation along a Boundary. The propagation of sound at grazing incidence has considerable practical importance. In gun ranging the source of sound is always on the ground, as is the receiver; a similar situation occurs for the great majority of outdoor acoustic problems. Thus the results of this study will be found to have bearing on such questions as altitude listening and velocity and intensity investigations.

The problem of the reflection of a plane wave from a boundary separating two semi-infinite media has received considerable attention. The medium above the plane $z = 0$ is assumed to be uniform; that below the plane has different properties and is also uniform. If, then, a plane wave in the upper medium impinges on this boundary, reflection will ensue, and there will also be a refracted wave which penetrates the lower medium. It is easily demonstrated that the boundary conditions are satisfied when (1) the normal particle velocities at the boundary in both media are equal at all times, and (2) the pressures at the boundary in both media are equal at all times—if the refracted and reflected waves are plane waves having the same frequency as that of the incident wave.

The reflection coefficient (for the amplitude) takes the form:

$$R = \frac{Z_2 \cos \theta_1 - Z_1 \cos \theta_2}{Z_2 \cos \theta_1 + Z_1 \cos \theta_2} \tag{8}$$

where

Z_2 = complex specific acoustic impedance of the lower medium

Z_1 = complex specific acoustic impedance of the upper medium

θ_1 = angle of incidence

θ_2 = angle of refraction.

The angle of reflection is equal to the angle of incidence.

Practically, plane waves never occur; they

are a mathematical fiction which can be only approximated physically. Consequently, the extent to which equation (8) applies to practical problems becomes a matter of experiment. It is indeed gratifying that the reflection coefficient given by equation (8) holds even for very rough approximations to the plane wave. Thus it has been found to hold for point sources of sound at relatively small distances from reflecting surfaces. This has led to the practice of applying the reflection coefficient to rays of sound.

There are limitations to the applicability of equation (8) which are immediately apparent

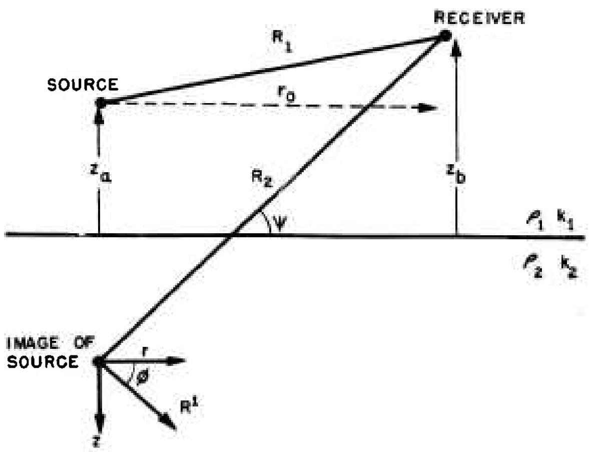


FIGURE 50. Propagation along a boundary.

on closer examination. Regardless of the relative magnitudes of Z_1 and Z_2 at grazing incidence ($\theta_1 = 90$ degrees), $R = -1$. (The reflected wave is equal in magnitude and 180 degrees out of phase with the incident wave.) Thus, for plane waves, the reflected wave completely cancels the incident wave, and there is no energy propagated along the boundary. On an experimental basis this is impossible, and one is led to the conclusion that the assumptions made in deriving equation (8) cannot be realized physically. However, this was recognized to be true at all angles of incidence, so one must conclude that, especially at grazing incidence (and for angles close to grazing), it is impossible adequately to approximate the plane wave conditions which were assumed, and indiscriminate application of equation (8) may lead to serious error.

To obtain a solution of the problem at angles near grazing incidence, it was necessary to set up the problem with a closer correspondence to physical reality. A point source of sound was assumed instead of a plane incident wave, the incident wave then being spherical. The form of the reflected wave was determined by the boundary conditions.

The problem here discussed has arisen in electromagnetic theory. Sommerfeld[38] attacked the problem first in 1909, and there has been considerable subsequent work. The analysis is rather involved, and it is fortunate that the acoustic case may be treated in a closely similar fashion. When the electromagnetic source is a vertical dipole, the boundary conditions expressed in terms of the Hertzian vector are similar in form to the acoustic boundary conditions expressed in terms of the velocity potential.

It was assumed that the material is isotropic. A porous material is characterized by the fact that a large part of its volume is taken up by air pores and channels. The solid material itself will have a density and rigidity which is high compared to that of air. Consequently, when an air sound wave impinges on the porous material, because the reflection coefficient of the solid material is likely to be very high, the wave will tend to remain an air wave, and energy will be transmitted mainly by the air in the pores.

It is evident that the acoustic properties of a porous material will be a function of frequency. One may also expect a behavior which is a function of the size of the pores or tunnels, wavelength being constant.

Suppose a point source to be a distance z_a above a plane, below which lies a medium which has a propagation constant k_2 and complex density ρ_2 (see Figure 50). The problem was to find the sound field at a point a horizontal distance r_0 from the source, and a distance z_b above the plane.

The theory developed led to interesting results concerning loss in intensity along a boundary. The loss is found to be proportional to the square of the frequency. One is thus led to

expect that a complex tone of low frequency will lose its harmonics at great distances to a much greater degree than air absorption, scattering, etc., would indicate. This is a generally observed phenomenon in atmospheric acoustics involving low-frequency sound waves. Under certain circumstances the theory indicates that there may be a consistent 12-db drop every time the distance is doubled, even when there is no absorption in the air. The 12-db value is the

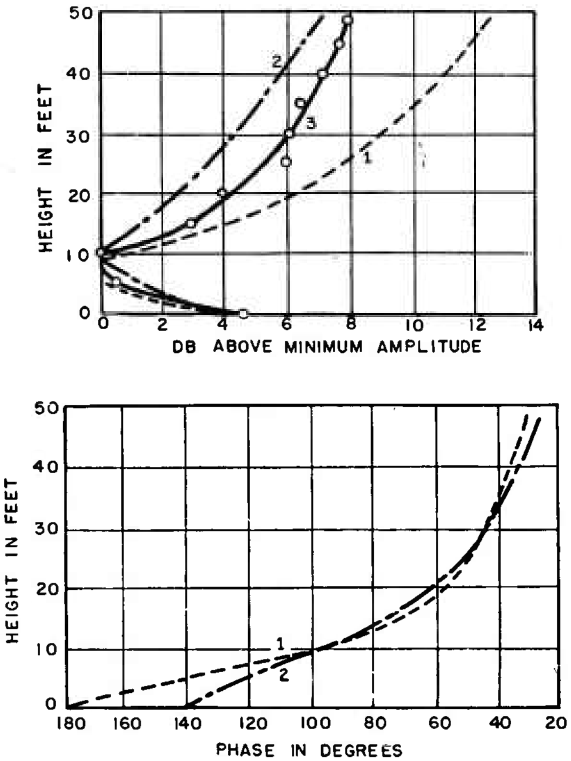


FIGURE 51. Observed and calculated phase-amplitude structure over dry ground.

sum of the effects of divergence from a point source and the boundary loss function.

The theory predicts a phase lag. This phase lag would become important in velocity measurements. For example, if a measurement of velocity were made using a 2,000-c wave by measuring the number of waves between 5 cm and 50 cm over Quietone, the source and receiver being at the boundary of the material, the error introduced by this phase lag would result in a value which was low by 7 per cent.

With the source taken at the boundary, the amplitude and phase structure for various receiver heights was calculated for air above Quietone and air above earth, the calculations in the latter case being based on measured values of flow resistance and porosity. The following results were obtained: (1) there is a minimum amplitude above the boundary; (2) the height of this minimum is practically independent of distance; (3) the rate of increase of the amplitude with height above the minimum is greatest at the greatest distance; (4) the height of the minimum increases with increase in wavelength; (5) the phase increases with height, the biggest increase occurring at the smaller heights; (6) at greater heights, agreement with classical theory is approached.

Figure 51 shows the observed and calculated phase-amplitude structure over dry ground. Curve 1 was calculated for a flow resistivity of 84 and a porosity of 54 per cent, and Curve 2 for a flow resistivity of 168 and a porosity of 54 per cent, values approximating those found experimentally for soil samples. Curve 3 is an experimental curve similar to Figure 45. It is seen that the experimental curve is bracketed by the calculated curves.

The rapid increase of the amplitude with height above the minimum at great distances suggests important applications to such fields as altitude listening.

Sound Transmission through a Rectilinear Vortex. This and the following section refer to theoretical considerations having a direct bearing on the source of wave front corrugations or irregularities.

The problem of sound transmission through a rectilinear vortex was treated, using hydrodynamical principles. It is shown that the observed phase fluctuations may well be due in part to the passage of a sound wave through simple vortices. In general, to be really effective in producing a time difference, the vortex center must pass across the line joining the source to the center of the base line.

Figure 52 gives a rough picture of what would be expected to happen when a sound wave originally plane approaches a vortex. The rotation is taken as counterclockwise. The dotted lines are the traces of the successive

equiphasal planes as they would be without the presence of the vortex. The full lines represent the actually distorted equiphasal planes. Since wave fronts are equiphasal surfaces, it is clear that the phase at P'' leads that at P'. On the other hand, if the amplitude at any point like P'' is considered to be made up of contributions from all parts of the immediately preceding wave front, it seems necessary that the intensity at P'' shall be less than at P', since the disturbances which reach P' will be in phase from more parts of the wave front near P' than is the case for P''. Stated another way, near P'' the wave disturbance is moving *out*, more or less like a *diverging* cylindrical wave, whereas near P' it is moving *in*, more or less like a *converging* cylindrical wave.

It seems reasonable to conclude that acoustic

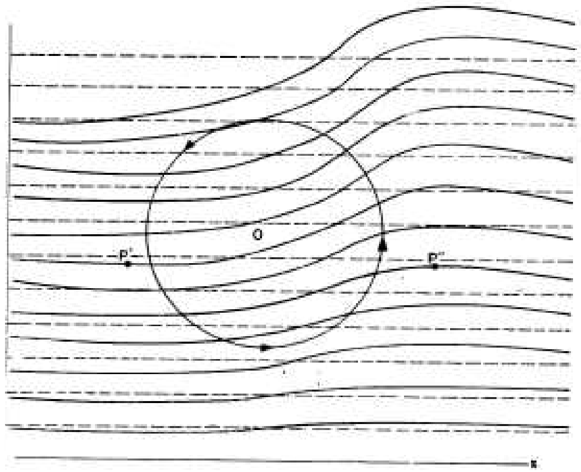


FIGURE 52. Phase diagram of a plane wave passing through a vortex.

wave front corrugations can be caused by the presence of simple circular vortices in the radiation field. It also appears that the distortion due to a vortex is such that an increase in phase is associated with a decrease in intensity and vice versa.

Scattering of a Plane Sound Wave by a Stationary Cylindrical Fluid Obstacle. A possible cause of variations in the wave front of a sound wave is the presence of regions of higher or lower temperature in the medium between the source and the receiver. These scatter the sound and hence can produce phase and intensity fluctuations at any pair of receivers.

A theoretical study was made of the phase and amplitude relationships resulting when a plane sound wave passes through a cylinder of air, at a temperature higher than that of its surroundings. Both the effect of distance on the magnitude of the phase and amplitude changes caused by the cylinder, and the relationship between the phase changes and the amplitude changes were considered.

In general the theoretical results confirm the hypotheses that the effect of a variation in the wave front tends to spread and later become inappreciable, and that an advance in phase is associated with a decrease in amplitude, and vice versa.

Hypothesis of Regional Effectiveness. An hypothesis was introduced stating that the wind is effective in influencing a microphone only while it is in a certain region about that microphone. Computations using some of the observed data yielded 56 ft as the region of effectiveness. (Only the order of magnitude is to be considered as significant.) Using some simplifying assumptions, a relation was derived which predicts that the mean phase deviation will increase linearly with the microphone separation for small separations, and will then increase much more slowly as the separation increases. This result agrees with the observed data. In its present form the hypothesis fails to afford a means of predicting theoretically the size of the effective region.

Conclusion. It is unlikely that a single influence is continuously predominant in causing acoustic wave front corrugations except under unusual meteorological conditions. However, regions of varying temperature and air circulation are probably frequent causes of wave front distortions. It seems quite possible that a theoretical basis for a phase-amplitude correlation exists.

5.6 ACCESSORY PROJECTS

5.6.1 Binaural Listening[13]

The object of this work was the development of a binaural listening device to be used as a

sound-ranging outpost and as an anti-infiltration device for the detection of enemy movements in the vicinity of patrols or important stations. The development of the binaural outpost (Binop) has already been described (Section 5.3). Discussion here will be limited to the anti-infiltration sets.

Advantages of an Anti-Infiltration Listening System. An anti-infiltration listening system is a device by which enemy movements may be detected over a wide range of territory by one observer without the need for personnel at the sentry positions. By this means information on enemy encroachment over a wide area may be

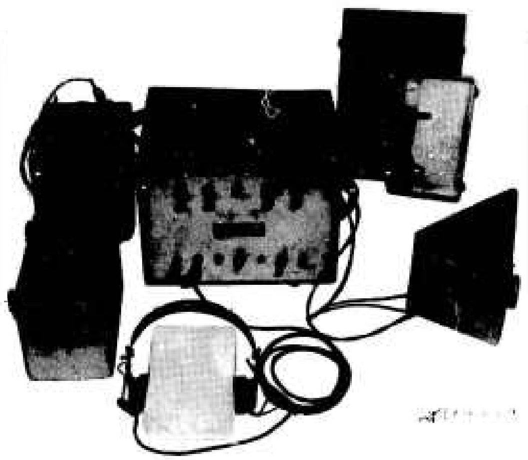


FIGURE 53. Anti-infiltration set, Model No. 1, set up for operation.

imparted to the most advantageous point without danger to personnel. Furthermore, the personnel required may be greatly reduced. The ability to distinguish particular sounds and to determine their nature is more desirable than determining the direction from which they came. The advantage of binaural listening for anti-infiltration purposes lies in its improved discrimination and characterization of sounds, especially in the presence of random background noise.

Method Employed. The anti-infiltration listening system is composed of two separate, single-direction transmission channels, each consisting of a microphone, an amplifier, and one receiver of a headset. The phase and frequency characteristics of the two channels are made identical, within small tolerances. The volume matching is part of the field calibration procedure. The two microphones are so located that they respond in practically the same manner as the human ears, each transmitting its signal to a corresponding ear of the listener. The effect of this arrangement is to transplant the listener aurally to the position of the microphone "head."

General Requirements. The idea of accurate location binaurally was never considered beyond the requirement that the binaural system have as satisfactory localization as the unaided ears. It was believed desirable that in the anti-infiltration device the microphone head be divorced from the amplifier to facilitate ease of installation and to reduce the expendability of the apparatus. This would permit the amplifier to be located at the listening station, thus simplifying the problem of operation and repair.

For anti-infiltration purposes the listening device should be capable of converting a wide range of sound levels into a narrow range of listening levels. This demand stems from the need to maintain relatively high listening levels for weak signals in order to improve their discernibility and to overcome the effects of possible high extraneous noise levels at the listening station. It was, therefore, necessary to incorporate high gain and a relatively large amount of compression in the amplifier.

Because the maximum output should be limited to a value which satisfactorily protects the listener's ears against unexpected loud sounds arriving at the microphones, some form of volume limiting should be incorporated.

A substantial reduction in frequency range over that used in the outpost system was found to be satisfactory.

Operating conditions demanded a microphone unit that was lightweight, portable, rugged, and sealed. The microphone head being the most expendable portion of the system, it was desirable to use relatively cheap microphone elements. A transducer usable both as a microphone and a receiver would materially reduce the problem of spare parts and servicing.

The microphone head should be designed to be light and compact, and to provide the best

possible binaural properties. Previous experimental results indicated that: (1) the baffle between the microphones should approximate the effective shadowing afforded by the human head; (2) the microphones should be spaced apart the approximate distance of human ears, an exaggeration of 10 per cent in separation being satisfactory.

Preliminary Anti-Infiltration System. The Western Electric type HA-2 receiver was selected for the first anti-infiltration set developed. The head, made of Celotex, was triangular

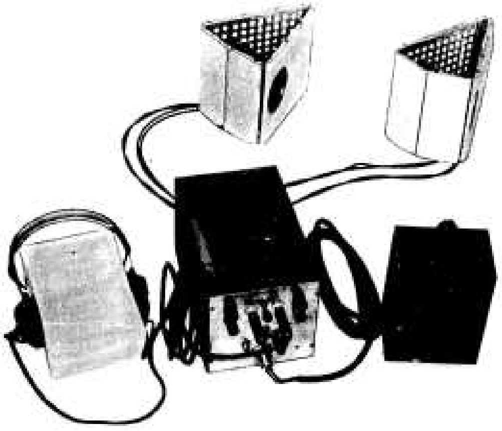


FIGURE 54. Anti-infiltration set, Model No. 2, set up for operation.

in shape, so designed as to be collapsible. The frequency response of the amplifier covered the range from 60 to 5,000 c; the response range of the receiver fell well within these limits. The required gain and compression were obtained. The maximum power output was limited to 6 milliwatts. Equalization of the gain and phase in the two channels was made possible. The first model is shown set up for operation in Figure 53.

Specific Military Requirements. The first model of an anti-infiltration system was given field tests at Fort Bragg, North Carolina. Representatives of the Field Artillery Board observed this demonstration and were favorably impressed. The Board believed, however, that certain improvements should be made. They recommended the development of a preliminary combat model, provided the following characteristics could be obtained: (1) decreased size and weight; (2) increased protection to the listener's ears against unexpected loud noises; (3) provision for multiple sentries for greater coverage with one operator; (4) suitable waterproofing and ruggedness of all parts, especially transducers; (5) a better microphone from the standpoint of frequency response.

Second Anti-Infiltration System. An anti-infiltration set fulfilling the above requirements was developed and a preproduction model was completed just prior to the termination of the contract. In addition to very much reduced size and weight, this model was equipped with:

1. An improved form of automatic volume control (compression);
2. A volume limiter holding the power output to 2 milliwatts but giving usable power for input signals in the range from 6×10^{-11} to 6×10^{-5} milliwatt;
3. A suitable switching arrangement for listening at will to any of three binaural sentry stations;
4. A sturdy waterproof head of sheet aluminum with glass wool covering;
5. The Marine Corps CW-59505 receiver unit, which is waterproof and may be used as a receiver or (with an equalizing system) as a microphone with a response between 100 and 4,000 c. This model, set up for operation, is shown in Figure 54. The total weight of the equipment shown is 21 lb. This set, completed in August 1945, was not submitted to the Field Artillery Board because of termination of the contract, but tests indicated highly satisfactory performance.

5.6.2 Analysis of Field Records[18, 19]

Analysis of field records from the western European front was undertaken in two different instances.

In the first instance the analysis was carried out at the request of the Field Artillery Board, which furnished some field records that had yielded a doubtful interpretation at the time they were taken. The Division acted here in a consulting capacity. The ballistic-burst method of determining the line of flight of a shell from the ballistic and shell-burst waves had recently

been developed. It was thought that application of this method, together with the experience members of the Division had had in distinguishing ballistic from gun waves, might make further analysis of these records possible. Should such prove to be the case, the conclusion would be that the ballistic wave should, when possible, be used in future field analysis of gun records.

In the second instance the Division requested certain field records for the purpose of analyzing them. It was hoped that such an analysis might be helpful in connection with a study which members of the Division were making of errors in gun ranging due to meteorological and terrain effects (see Section 5.5).

Use of the Ballistic Wave in Gun-Ranging Analysis

Data Supplied. A letter of December 14, 1944, from the Field Artillery Board included the data on a series of nine acoustic locations made in France and Germany. Of these nine locations, three had already been confirmed by other methods, either by occupation of the territory or aerial reconnaissance. The films for the six unconfirmed locations were included for further analysis. The sound records supplied were taken by the 13th Field Artillery Observation Battalion operating in the vicinity of Vicht, Germany, during the period November 5-9, 1944. Two straight bases, each containing six microphones, separated by 4 sound-seconds, were used.

Procedure. In carrying out the analyses the procedure was generally as follows:

First the traces produced by each microphone were studied, noting times of all breaks. Then all such data were treated as if the waves producing the breaks might have been ballistic, using the earliest time of arrival as the basis from which all time differences were computed. These computed time differences, corrected for temperature but not for wind, were then converted to meters and, with these distances as radii, circles were drawn about the corresponding microphone positions. Smooth curves tangent to families of these circles represent approximately the traces of the various possible waves on the ground and, therefore, indicate which breaks belong together.

The shape of the trace obtained by treating the data as described may give additional information as to the nature of the sound source. Curves obtained in this manner from ballistic waves, gun waves, and shell waves will, in general, be either parabolas or circles. It may be stated that when the curve is a parabola, the sound source causing it must have been a ballistic wave. If, however, the curve is indistinguishable from a circle, it may correspond to a wave from a stationary source such as a gun or shell burst, or to a ballistic wave with an essentially circular ground trace. The shell-burst wave could usually be identified by its much later arrival time, whereas the gun wave and ballistic wave could often be distinguished by making standard plots of each on the M-1 board or its equivalent and examining the resultant cat's cradles. Each type of wave gives a characteristic cat's cradle.

The next step in the analysis was to determine whether the shell burst was in any way correlated with the gun. The gun was plotted by the standard method. The shell burst was also plotted in the same manner and was located in one or the other of two symmetrical positions in front of and behind the base line. (The sound-ranging operator in the field probably knew which of these two positions was the correct one by means of data not forwarded to the Laboratory.) A correlation of the time of flight and the range from gun to burst for each of these two particular locations should indicate which position is correct. The line of flight of the shell may also be determined for a given shell-burst position and ballistic wave. This line of flight should pass through or near the gun location, if the interpretation of the various waves is correct.

It may arise that more than one gun, ballistic, or shell-burst wave is present, further complicating the analysis, but the method outlined was generally successful even in such cases. In certain cases it was even possible to postulate the type of gun firing from its range and shell velocity.

Results and Conclusions. The six films were analyzed. Five of them yielded definitely valuable results; the sixth yielded indications which would require corroboration by further

data before actual use. The analyses were made without the assistance of much auxiliary data which would obviously have been known to an observer in the field, such as the general target area and probable type of gun and shell. Such data might enable an observer to decide between some of the alternatives which presented themselves. Much of the information obtained by this analysis could have been determined by inspection in the field had the sound-ranging bases been equipped with microphones having an upper frequency limit of 50 or 60 c (unmodified T-21-B microphones were used). The method developed for the analyses yielded, in several cases, quite different diagnoses from those obtained by inspection in the field. It was believed some features of this method are sufficiently simple and yield sufficient information of practical value to be considered for standardization. (Use of the ballistic and shell-burst waves for determining the line of fire and caliber of the gun has since been incorporated into the War Department Field Manual FM 6-120.)

Meteorological and Terrain Effects in Gun-Ranging Analysis

As a result of having seen some British data which was insufficient to do more than to indicate a trend, the Division requested further data to investigate the question of the relationship between the type of error—range or line—predominating in sound ranging and the type of meteorological conditions existing at the time the measurements were made.

Data Supplied. The analysis was carried out on the data of Army Ground Forces Reports C-Misc-29 and 30, ETO, which were forwarded via the Field Artillery Board on December 22, 1944. The data were taken by the 3rd, 7th, 8th, and 16th Field Artillery Observation Battalions and included such items as time of firing, location of base, sound-ranging location, sound metro message, comparison of sound location with adjusted coordinates of enemy batteries, comparison of photographic interpretation locations with confirmed sound locations, flash-ranging location, and report on effect of fire. Not all these items were supplied in each case. Unfortunately, the equivalent of a map survey position of the gun appears to have been unknown for a large number of the shots for which data were included, making the data inadequate for carrying out the type of analysis originally proposed. However, the data were sufficient to yield information of value to sound-ranging officers.

Conclusions. No clear relationship between the meteorological conditions present and the type of error—range or line—predominating in sound ranging was revealed by the analysis of the data. The desirability of analyzing data better adapted for this study was pointed out.

A study of the data indicated clearly the necessity for frequent meteorological messages when conditions are changeable, but yet not so unstable that the application of meteorological corrections is unwarranted. When conditions are stable, the present intervals are satisfactory.

If a sound source is located in or immediately behind a village, larger errors should be expected than for sources in the open.

Two methods of computing effective winds for sound ranging were outlined, both of which use the present standard weighting but obtain a more accurate effective wind by employing vector rather than scalar addition. A comparison of the values of the effective wind computed by the new methods sometimes gave results widely different from those obtained by the standard method, although in many cases they were nearly identical.

Recommendations. The following recommendations should be considered tentative in view of the small amount of data upon which they are based:

1. The question of the relationship between the type of error—range or line—predominating in sound ranging and the type of meteorological conditions existent at the time the measurements were made should be studied further.

2. Meteorological messages should be taken more frequently when the meteorological conditions are changing rapidly.

3. Caution should be used in assessing the accuracy of sound locations which indicate that a gun is in the vicinity of a village, since relatively poor sound locations resulted in most cases where the gun was located either in or

near a village so that the sound path is over buildings.

4. The method of calculating the effective wind for sound ranging should be investigated.

5.6.3 Proposed Method of Sound Ranging Eliminating Meteorological Corrections[23]

In the standard method of sound ranging it is necessary to correct the arrival times of the sound wave at the microphone base for the effects of the existing meteorological conditions. In standard practice these meteorological corrections are computed empirically from pilot-balloon ascensions and from ground temperature measurements. This procedure immediately gives rise to certain possibilities of error, for the following reasons:

1. The pilot-balloon ascensions and ground temperature measurements are ordinarily made at intervals of about one hour, on the assumption that the meteorological structure of the atmosphere varies slowly during this interval, and also that the wind and temperature vary with height uniformly over the region in which sound-ranging measurements are made. Actually, it appears highly probable that neither of these assumptions is true.

2. Even if the existing meteorological structure has been determined accurately, it is still necessary to reduce this structure to an equivalent wind and temperature which are uniform with height. The procedure for doing this is entirely empirical (see Section 5.3).

The purpose of this work was to formulate a new method of sound ranging which would require no corrections for the effects of wind, temperature, or curvature of the wave front. In addition to its possibilities as a method of sound ranging, such a method could also be used as a very powerful tool in the measurement of effective meteorological conditions and of their effects on the shape of the wave front.

Principles Involved. The development of this method was started as a result of a British report forwarded by the OSRD Liaison Office (Loga 6914, Appendix II). This report gives the basic theory of this method, employing the method of least squares. The new method uses a two-dimensional microphone array and requires six or more microphones. By determining the time of arrival of the sound wave at each of these microphones with respect to an arbitrary time zero, it would be possible to compute directly the position of the sound source with respect to a known position in the target area (see Figure 55). There are six variables concerned:

1. The distance x in the X direction of the actual source from the known point;

2. The distance y in the Y direction of the actual source from the known point;

3. Value of the effective wind component in the X direction (α);

4. Value of the effective wind component in the Y direction (β);

5. Still-air sound velocity for the existing temperature;

6. Total time of travel of the sound from the source to the microphone.

It will be seen that time measurements at each of six or more microphones would furnish sufficient data to eliminate the last four of these variables and solve for x and y.

If this method were used as a tool for the study of effective meteorological conditions and of their effects on the shape of the wave front, the three variables which would be solved for are:

1. Component of the wind in the X direction;
2. Component of the wind in the Y direction;
3. Still-air sound velocity.

From these results it would be possible to compare the actual effects of the meteorology existing during the sound travel from source to microphone array with that computed by the present method or any proposed improvement thereof.

Equipment Required. To apply this method in the field, the following equipment would be needed: eight sound-ranging microphones to form the array shown in Figure 56; one oscillograph with eight recording elements, such as the standard GR-3-C recorder currently used by the U. S. Field Artillery Observation Battalions; plotting board for determining locations; and a table giving values of certain constants involved, as computed for a series of reference points selected in the area within which enemy guns might be expected.

Equipment Eliminated by this Method. The use of this method would eliminate the following personnel and equipment at present necessary in the standard method of sound ranging: meteorological section and equipment necessary to determine effective sound-ranging meteorological conditions, charts for determining the meteorological corrections for the effects of wind and temperature, and charts for the de-

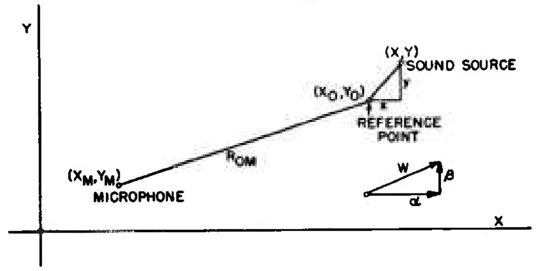


FIGURE 55. Method of sound ranging eliminating meteorological corrections.

termination of corrections for wave front curvature.

Sound-Ranging Procedure. The actual field procedure to be used in the application of this method is outlined below.

The arrival times, $t_1, t_2, \cdots t_8$ of the sound wave at each microphone are read from the oscillogram with reference to an arbitrary zero time.

It is necessary to make a rough determination of the location of the source, so that the reference point closest to the actual gun location can be selected.

The values of the quantities x and y can be calculated as follows.

$$x = A_{11}t_1 + A_{21}t_2 + A_{31}t_3 + A_{41}t_4 + A_{51}t_5 + A_{61}t_6 + A_{71}t_7 + A_{81}t_8 + B_1$$

$$y = A_{12}t_1 + A_{22}t_2 + A_{32}t_3 + A_{42}t_4 + A_{52}t_5 + A_{62}t_6 + A_{72}t_7 + A_{82}t_8 + B_2$$

where the A's and B's corresponding to the reference point selected are obtained from the table described in Section 5.6 under *Equipment Required.* The actual calculation in the field is then reduced to the multiplication of sixteen A values by the appropriate t's and the summation of the resulting products to give the x and y values, as indicated in the above equations.

The actual location is then obtained by plotting these x and y increments from the selected reference point. This location gives the most probable position of the sound source and takes into account the effective wind and temperature, although these quantities are not solved for explicitly.

Investigation of Major Meteorological Structure. It has been indicated that considerable inaccuracy may be introduced into sound-ranging measurements by the method of determining the effective sound-ranging meteorological conditions as based on pilot-balloon ascensions. From an array of the type shown in Figure 56 it would be possible to determine the most probable value of the two components of the instantaneous effective wind and the most probable value of the instantaneous still-air sound velocity. By taking a series of sound records for sources at various ranges and azimuths with this two-dimensional array and simultaneously determining the effective sound-ranging meteorology by pilot-balloon ascensions, it would be possible to determine, by a comparison of the results of these two methods of making meteorological measurements, the following: (1) whether an effective wind-and-temperature structure exists which is constant over any appreciable area and time; (2) if such an effective meteorological structure does exist, whether the present method of determining this structure by pilot-balloon ascensions and ground temperature measurements gives a sufficiently accurate evaluation of it; (3) if the present method of determining sound-ranging meteorology is unsatisfactory, whether some improved method of weighting meteorological data can be devised which will give a better approximation to the effective conditions as measured by the two-dimensional array.

Investigation of Micromet. In addition to this problem of the major meteorology, there are also fluctuations from these average conditions which can occur in a period of time of the same order of magnitude as that during which the sound propagation occurs (see Section 5.5). This two-dimensional array presents a method of determining whether these rapid fluctuations are of importance in their effect on sound-ranging measurements.

Thus, if one of these two-dimensional micro-

phone arrays could be set up with a reference point at a known position with respect to it, then if a series of shots were set off at this reference point and the locations determined by the method described above, it is seen that the values of x and y should be zero. Any deviation could be attributed to the fluctuations in the meteorological conditions.

As an alternative, the three effective meteorological factors—(1) the component of the wind along the sound path, (2) the component of the wind at right angles to the sound path, and (3) the effective velocity of sound over the sound path—could be determined for this fixed position of the source. If shots were fired every minute or every two minutes, the variation of these factors with time could be determined.

Summary of Results. No actual field tests of the method were made, although a number of theoretical cases were calculated. The method has the following applications: (1) as a practical field method of sound ranging without the use of meteorological corrections; (2) as a research method of determining the effective major meteorological structure for sound ranging; (3) as a research method for the investigation of the effect of fluctuations in the meteorological conditions upon the accuracy of sound ranging.

5.6.4 Sphinx[24]

In the war in the Pacific the enemy frequently took to hiding in caves, making the locating of such caves an important problem. As a satisfactory solution had not been found, the Armed Forces requested the Division to investigate the possibility of locating such caves by acoustic means. Work on this project was abandoned with the ending of World War II, but results of a preliminary nature were obtained.

Principles Involved. A cave is an enclosure with an opening to the air; as such it will be resonant at certain acoustic frequencies which are a function of the cave's dimensions. Consequently, if a complex sound wave containing energy in the correct frequency regions—such as might result from an explosion—impinges on the opening of the cave, these resonant frequencies will be excited and radiate sound selectively. It was the purpose of this investigation to determine if this reradiated sound had sufficient intensity and was sufficiently unique in character to be distinguishable from normally reflected sounds. If this was so, it would be possible to sound range on caves by setting off a blast in their neighborhood.

Theoretical Considerations. The results of a theoretical study of this problem indicated that when the air in a cave is actuated by an external sound, low-frequency sounds are generated by the action of the cave as a Helmholtz resonator,

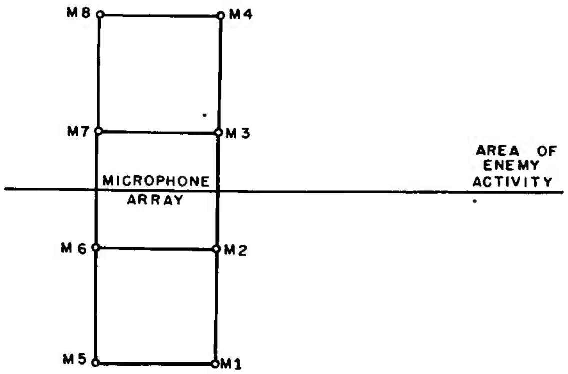


FIGURE 56. Two-dimensional microphone array.

and higher-frequency sounds are generated by internal reflections (reverberations). Intensity considerations favor working at low frequencies. Assuming the actuating sound to be an impulse produced by an explosion, it was computed that the sound should be of sufficient duration to excite the air in the cave, but not so long as to make the identification of the sound from the enclosure difficult due to troublesome reflections. The possibility of exciting the cave by means of an earth-borne wave was also considered worthy of experimental investigation.

Equipment. Two enclosures were used. One was a 3-ft cubical plywood box with a 20-in. diameter hole cut in its face. This box was used mainly to test equipment and to give an indication of the factors which might be expected in later field experiments. The second enclosure investigated was a concrete bunker,

whose inside and outside dimensions are indicated in Figure 57. (The openings at B and C were closed in the final tests.) While this is not properly a cave, a sufficient indication of the feasibility of sound ranging on caves should be obtainable by a study based on this bunker.

The microphones used in these tests consisted of T-2 and WE type 633 microphones. The T-2 microphone is the crystal type developed by the Division (see Section 5.4). It has a low-frequency cutoff of about 3 c. For the frequency range from 50 to 500 c the Western Electric type 633, a low-impedance, dynamic type of microphone, was used.

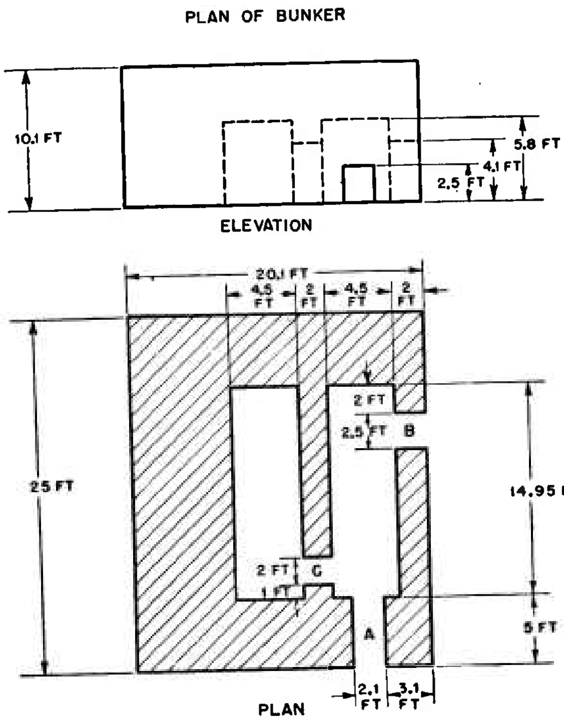


FIGURE 57. Plan of bunker.

Special types of amplifiers were required for each of the microphones. It was necessary to design the units with a volume limiter having a very sharp cutoff (1) to avoid damage to the oscillograph strings from signals with too much amplitude, and (2) so that the large signals from the direct sound of the bursts would not block the amplifier for more than 50 milliseconds.

A rapid-record oscillograph (the six-string galvanometer type using a 70-mm photographic paper for recording the traces) was used during these tests.

Procedure and Results. Field experiments were performed in which an M-1 rifle was fired 40 ft in front of the plywood box, first with the hole open and then with it closed. With the hole open, the oscillogram showed the sound of the rifle followed by the waves reflected from the box and a reverberant tail. With the hole closed, the reverberant tail was missing. Thus it was possible to detect the "cave" reverberations (about 180 c) for distances from 50 to 100 ft in front of the open box. However, with this sound source it was not possible to excite the frequency of the box sufficiently as a Helmholtz resonator (43 c in this case).

Subsequent tests were made with the bunker, which approximated a full-sized cave. Commonly available explosive sounds were used. The oscillograms showed evidence of resonance phenomena when the microphones were 3 ft in front of the entrance but gave no indications of resonance when located 30 ft or more away (see Figure 58, in which A, B, *1*, *2*, and *3* indicate various microphone positions). It was evident that both the reverberation and resonant frequencies were insufficiently excited to produce an intensity detectable at any significant distance from the cave. Reflection from the surrounding terrain and extraneous objects was of sufficient intensity to mask completely the cave resonance sounds. It is believed that this may be due to the small energy content of the explosion in the desired frequency range, i.e., below 50 c, and that work should be initiated

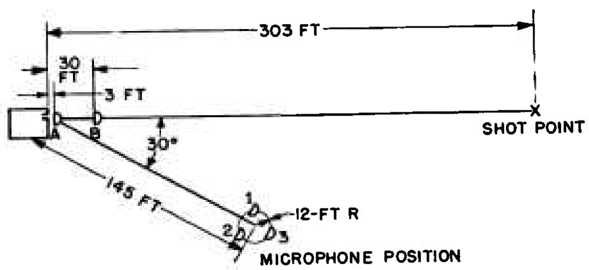


FIGURE 58. Survey of bunker, microphones, and shot point.

to obtain explosive sources having high energy content in the frequency range from 5 to 50 c.

The problem was investigated only superficially in the short time available. Its importance may warrant further investigation.

5.6.5 General Consulting

In a few instances, problems were undertaken by the Division at the specific request of the Armed Forces. This was the case with work on the ballistic-burst method, the analysis of certain field records, and Sphinx. In each of these cases some work on the subject had already been done by others, and the Division was requested to continue the investigation.

Frequent conferences attended by members of the Division and military personnel were held. At such conferences the military men presented some of their problems, and these were then discussed. Members of the Division always considered themselves available for call to such meetings. Many of the particular projects discussed in this report originated in this manner.

During many of the field tests of methods and equipment which were conducted at Fort Bragg, North Carolina, Fort Sill, Oklahoma, and Quantico, Virginia, members of the Division worked closely in the field with military personnel, both officers and enlisted men. Many friendly contacts were established. In this way members of the Division learned at first hand some of the problems encountered by the men in the field. Often the Division members were able to help the military personnel to understand the sound-ranging equipment better and to use it more effectively. The liaison officers to the Duke project have emphasized that this education of sound-ranging personnel was one of the most important contributions rendered by the Division.

5.7 PRESENT STATUS OF THE SUBJECT

The military importance of sound ranging has long been accepted. The work described in this report should make it clear that there was a definite need for research in this field, and that this research produced valuable results. However, it should be emphasized that the possibilities for research along this line were by no means exhausted, nor were all the individual projects undertaken followed through completely. Many were left incomplete at the termination of the contract. Others were abandoned to concentrate on other work of greater urgency, or because they would not yield results of immediate use in a war nearing its end. The majority of such projects deserve further study, both from the purely scientific and from the military standpoint.

Pure research on fundamentals is a necessary background to the best results in all practical development work. Such research requires a long-sustained program, usually impossible during the urgency of a war period; it must be continued during times of peace.

Scientific advances predetermine new types of warfare, making new research on the military applications of a given field always necessary. Sound is no exception. For example, rocket projectiles require a different method of sound ranging from that applicable to ordinary guns. Again, an underground type of defense presents a problem entirely different from that of usual ground warfare.

Research on a particular problem frequently suggests new lines of development quite different from that of the original problem. Thus new methods of offense as well as of defense may suggest themselves, and certain methods now in use may be found not worth the effort and expense they entail.

It is advantageous if new methods and equipment can be exhaustively tested and studied in non-combat action, where failures or mistakes can be discovered without costly results.

Types of Bases. The study of different types of bases showed that the choice in a specific instance must always depend on circumstances. It was never universally agreed whether a one-dimensional or a two-dimensional base was preferable. Further investigation of this problem is required.

Microphones. The work of the Division showed that there was a lot of room for improvement in the types of microphones used in

military sound ranging. Response, durability, and portability were improved; it is quite possible that other improvements could be made through further research along this line. For example, at the termination of the work on the T-2 lightweight crystal microphone, it was possible to recommend additional changes, such as a more waterproof type of plug. Time did not permit these suggestions to be investigated.

Binaural Outpost and Binaural Listening. The binaural outpost system developed by the Division was tested by the Field Artillery Board and found to perform the functions for which it was designed. However, it was never tested in combat because it was decided that it was more important to transport other equipment, deemed more necessary, to the fighting fronts. The possibilities of this outpost system should be more fully investigated. The binaural anti-infiltration set reached the stage of a preproduction model and deserves further development. Further improvements were suggested by the Division, such as tropicalization and the acquisition of a cheap, rugged microphone with a flat response. The equipment should be given thorough field tests.

Computing. New systems require new methods of computing. There are many possible methods that could be applied to a given system, and only investigation can show which is most practical. It was felt by the Division that the nomogram was a definite contribution, but because of the termination of World War II, its possibilities were never fully realized by the Field Artillery. Further education in its efficient use seems necessary.

Ballistic-Burst Method. The advantages of this method were realized by the Field Artillery, and it is now included in Field Manual (FM No. 6-120). Its further application to ranging on rocket projectiles and new types of guns is worthy of attention.

Templates, Grids, Cases, etc. The trace-reading template proved definitely helpful. The Lucite plotting grids and accessory equipment (Lucite fans, microphone base, etc.) were very favorably received by the Field Artillery Board, but termination of World War II prevented their being tested thoroughly. Various types of cases were designed for these grids, as well as for the nomogram, Dodar, and microphones. The case for the Dodar incorporated several improvements over existing types of cases for military equipment, especially in ruggedness and watertightness. The features of this design should be applicable to other types of portable instruments.

Dodar. The value of the Dodar was shown in the Iwo Jima campaign. However, in subsequent combat use, it did not make as favorable a showing. It was felt by those most familiar with it that it was not handled in the most efficient way. This was partly because time did not permit sufficient education of the military personnel in its use and maintenance. A new method is often not generally accepted until it has proved itself. This should now be possible. Further, as mentioned earlier, a new ultralightweight Dodar system was developed near the end of the Division's contract. This system was demonstrated in its experimental stage and proved worthy of further development. The increased mobility of modern warfare emphasizes the need for a system such as that furnished by the Dodar.

Sphinx. Time did not permit anything but a preliminary investigation of this problem. The increased tendency in modern warfare to go underground puts great importance on the location of enemy caves, dugouts, and other shelters. The fact that resonance vibrations in such air cavities can be detected at all, even though at only short distances from the entrances is significant; it suggests further investigation, using different sound sources (preferably those with more energy concentrated in a low-frequency band) and different types of receivers. The possibility of using earth-borne waves is also considered worthy of further study.

Meteorological and Terrain Effects. The importance of meteorological effects in sound ranging should be clear. As has been pointed out, these effects may be divided into those produced by the major meteorological structure and those due to micrometeorological effects. Each must be considered serious and, at times, very troublesome. It was felt by the Division that the greater emphasis placed by it on micrometeorological effects was a very important con-

tribution to the subject of sound ranging. However, it has been pointed out that this study could only be looked upon as a beginning, and that an exhaustive investigation of the subject must be undertaken as a long-term research program. It was recognized that the greatest possibility of reducing meteorological errors may be not in seeking improvements in present sound-ranging methods, but in finding radically different ones which might utilize other, now unused aspects of transmission phenomena. An example of this is the proposed method of sound ranging discussed in Section 5.6. The value of the theoretical and experimental work on sound propagation in air above a boundary surface should also be stressed, as the results of this work suggest a modification of existing theories and interesting future applications. It is hoped that this fundamental physical research will be continued during peacetime, not only for its military value but also for what it may add to scientific knowledge.

Chapter 6

INFRARED GAS DETECTORS AND ANALYZERS

By *Clark Goodman*[a]

6.1 INTRODUCTION

Although detection, identification, and measurement of gases by study of their spectral absorption bands have been laboratory procedures for many years, development of portable and easily operated apparatus using infrared absorption bands of gases as the means of detection has been accomplished only recently. Infrared gas detectors may be either nonselective or selective. For either type of apparatus, a response time of a few seconds is obtainable.

The military interest in gas detectors arises from certain field situations which involve poisonous gases as weapons, and certain ventilation problems of closed equipment which involve poisonous gases as incidental products of gunfiring or other operations. It is evident that any attack on these problems requires suitable means for detection and for measurement of concentration of the particular gases involved. The principle of infrared detection of gases was selected for development because of its inherent rapid response and its high sensitivity and high selectivity for certain gases, particularly carbon monoxide (CO) and carbon dioxide (CO_2). Furthermore, the fact that its output is electric provides the possibility of using a direct-reading meter or chart recording of the final indication. All the possibilities of this type of apparatus have not been exploited, but equipment now available appears to be particularly useful for ventilation studies and for certain laboratory problems in testing of gas masks. It certainly could be used as a device to warn of the accumulation of dangerous gases in closed equipment; in fact, it has been used in tanks and also to detect CO_2 in submarines. It does not, however, appear applicable to field use as a detector of war gases.

Nonselective types are designed for detecting and measuring a small quantity of a gas when no other absorbing gases are present, or when only one constituent of a gas mixture is changing concentration, and will detect a large number of gases to limits of a few parts per million. These detectors are particularly useful for study of the breakdown of gas masks, measurements of water-vapor concentrations in oxygen, study of the change in concentration of a "tracer" gas in ventilation work, etc.

Selective-type instruments are designed for detecting and measuring concentrations of CO_2 or CO (or certain selected gases) in the presence of other absorbing gases. They are made in such a way that they will ignore changes in concentration of most gases other than the one being investigated. For example, the carbon monoxide in the breathing zone of a gunner can be correctly measured in the presence of ammonia, water vapor, carbon dioxide, oxides of nitrogen, and the other gaseous products of gunfire. Such instruments have been or may be used for CO analysis in tanks, determination of ventilation rates in tanks, survey work in aircraft, study of submarine atmospheres, etc.

6.2 GENERAL PRINCIPLES OF INFRARED GAS DETECTORS

Infrared gas detectors make use of the infrared absorption bands of certain gases. These bands are characterized by certain frequencies at which the gas absorbs energy. In a simple way, one may think of a space filled with the gas as containing a great number of oscillators composed of masses of springs, corresponding to the atoms and the chemical bonds by which they are held together to form gas molecules. If radiant energy containing the proper frequency components passes through a space containing such oscillators, they will be set in motion. Their energy of motion is absorbed from those components of the entering radiant energy having the same frequency; therefore,

[a] Technical Aide, Division 17.

the radiant energy leaving the space will be deficient in those same frequencies, giving rise to the absorption bands. These bands are in the long-wavelength range of the radiation spectrum, which is beyond the visible range, i.e., the infrared (or heat spectrum). All dipole molecules (i.e., those composed of two unlike chemical atoms, such as CO and HCl) have infrared absorption bands; gases composed of like chemical atoms (such as H_2 and O_2) do not.

The following brief list indicates some of the combinations which can and which cannot be selectively measured in devices of this type by their infrared absorption.

A C-H gas can be detected in the presence of CO, CO_2, SO_2, and the elemental gases, such as O_2, H_2, and N_2.

CO can be detected in the presence of CO_2, H_2O, NH_3, C-H gases, elemental gases, and most others.

Similarly, CO_2 can be detected in the presence of CO, H_2O, NH_3, C-H gases, and most others.

Gases which have overlapping bands (one of which, therefore, cannot be selectively detected in the presence of others) include NH_3 and H_2O; H_2O and the C-H gases; NH_3 and the C-H gases; one C-H gas in another (i.e., ethane cannot be selectively detected in methane).

Investigations of infrared spectra and any application of their properties involve the use of direct radiation detectors. The spectral range is entirely outside that in which visual observation or photography is possible; neither can such things as photoelectric cells or barrier-layer cells be used. The radiation detectors commonly used for infrared work are radiometers, bolometers, or thermopiles. The applications discussed here use a thermopile, which is a series of thermocouple junctions connected in series, so that their voltages add up; such a thermopile is responsive to extremely small amounts of radiation. By measuring the output voltage of a suitable thermopile with a sensitive galvanometer or with a d-c amplifier, it is possible to detect and measure or record the small changes of energy associated with changes in absorption in the infrared bands.

Important practical limitations arise because many materials (in particular, glass) are not transparent to infrared radiation; consequently, lenses cannot be used and any focusing is usually done with concave mirrors. Windows are commonly made of rock salt, fluorite, or lithium fluoride, depending on the wavelength range to be used, as these materials transmit much farther into the infrared than glass.

6.3 SELECTIVE GAS-ANALYSIS APPARATUS

6.3.1 Model IV

A gas-analysis apparatus of the selective type was developed at Johns Hopkins University[1-5, 7]

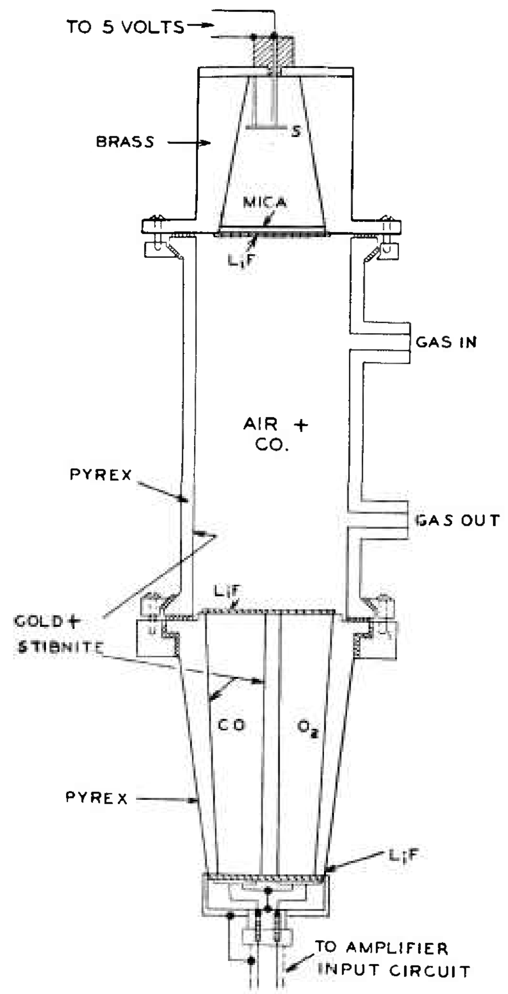


FIGURE 1. Essential parts of the infrared selective gas analyzer, arranged for determining CO in air.

and placed in pilot manufacturing by the Leeds & Northrup Company.[6, 7] The essential parts of the gas analyzer proper are shown in cross sec-

tion in Figure 1. This unit of the apparatus is a tubular assembly containing four essential parts:

1. A brass chamber containing the source *S*, which is Nichrome spiral, heated by an electric current.

2. The sampling chamber, which is a Pyrex-glass tube with inlet and outlet branches. This tube is gold plated on the inside and the gold is, in turn, covered with an evaporated layer of stibnite, which protects the gold surface from absorption of gas and maintains the infrared reflectivity.

3. The filter cell chamber, which is a Pyrex-glass cone with a partition down the center dividing it into two semiconical parts. This cone, like the sampling chamber, is gold plated.

4. The thermopile chamber which holds the differential thermopile. There are lithium fluoride windows between source and sampling cell, between sampling cell and filter cell, and between filter cell and thermopile. Since the characteristics of the apparatus are critically dependent upon the concentration of gases in the filter cells, these have to be closed almost as completely as if they held a high vacuum.

The electric system is shown in Figure 2. The output from the differential thermopile and

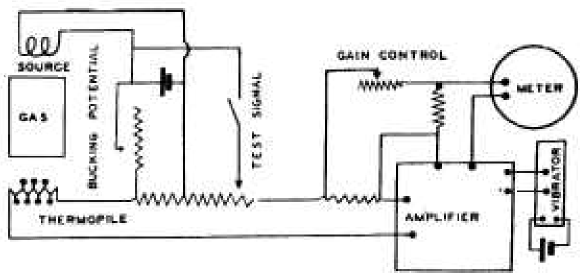


FIGURE 2. Basic circuit of selective gas analyzer.

balancing network is fed into a chopper amplifier, which, in effect, converts the d-c output from the thermopiles to a small a-c voltage, amplifies that voltage, and then reconverts the output back to direct current, so that it can be used to operate a d-c recording milliammeter (with full-scale deflection for 1 ma).

The various resistances and adjustments which are shown are those necessary for (1) setting the bucking potential and thermopile shunt, thereby balancing the thermopiles under certain standard conditions, (2) setting the heating current through the source to a standard value, and (3) applying a standard test signal to the amplifier. (Thermopile balance is quite critically dependent upon the temperature of the radiation source, and that source must be supplied from a well-charged battery and dropping resistor to maintain a standard potential.) A separate 6-v battery supplies the power for the chopper amplifier.

The gas analyzer, a small flow meter to indicate gas flow, the associated components of the electric circuits, and the chopper amplifier and its power-supply vibrator unit are assembled together in a box (Figures 3 and 4) measuring $14\frac{3}{8}$ in. high by 16 in. long by $9\frac{1}{4}$ in. wide and

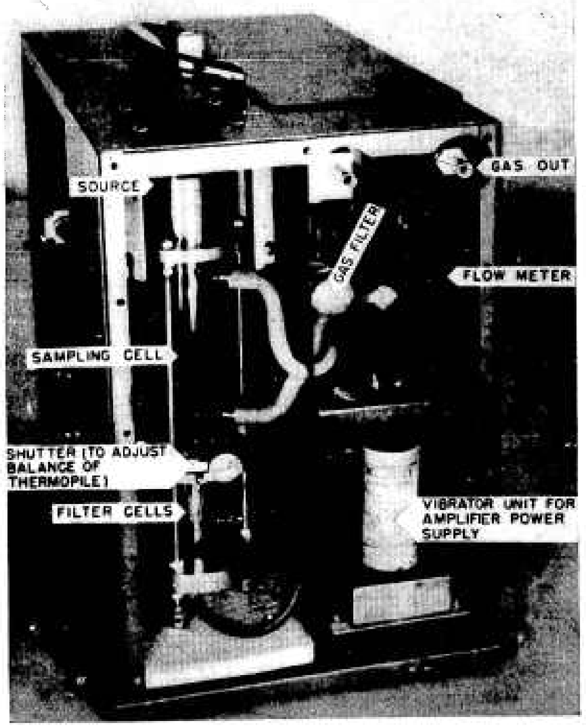


FIGURE 3. End view of carrying case holding the infrared gas analyzer and its associated electric equipment.

weighing 45 lb. The complete equipment, including battery box (to hold two 6-v automobile-type storage batteries), analyzer, and recording output meter, is shown in Figure 5.

The sensitivity of this apparatus is limited

by the background noise and, therefore, depends upon the conditions under which it is used. In laboratory tests, with only mild temperature fluctuations and relative freedom from drafts, the apparatus now built will reliably and clearly detect CO selectively down to concentrations of about 0.005 per cent, as is indicated by the sample chart from the recorder, shown in Figure 6. This apparatus has been designed specifically to measure CO in the range from 0.01 per cent to 1 per cent. It is possible that under field conditions, with more exposure and wider temperature fluctuations, the output will be less stable, which may materially raise the lower limit.

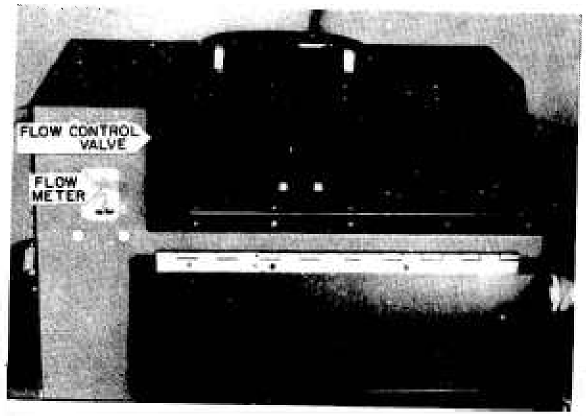


FIGURE 4. Carrying case containing the infrared gas analyzer and the circuit that permits electric measurements of heat radiation absorbed by selected gases.

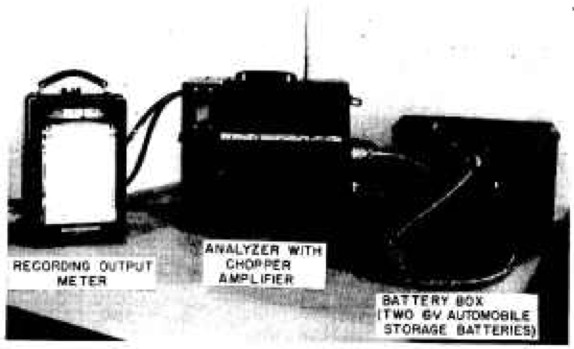


FIGURE 5. Complete infrared gas analyzer, recorder, and storage batteries.

The present apparatus is not suitable for measuring CO or CO_2 concentrations greater than about 1 per cent, but a shorter sampling cell would enable the instrument to measure higher values.

6.3.2 Model V

The apparatus just described was known as the Model IV gas analyzer. In September 1944, after Edgewood Arsenal had made the necessary arrangements with NDRC, the Chemical Warfare Service placed an order with Leeds & Northrup for twelve gas analyzers. Production difficulties resulted in a practically new design, although the outward appearance and general construction of the instruments were the same as Model IV. One essential difference was that the motor-driven chopper amplifiers with the vibrator plate supply were no longer available. Consequently, General Motors Series 400 motor-driven amplifiers were used instead. These required a somewhat different circuit and employed a dynamotor as a plate supply instead of the previous vibrator type. The thermopiles used were made with bismuth versus silver wire. Insulating strips were mounted inside the battery boxes to insulate the batteries from the metal boxes. The operation of these instruments was essentially the same as the Model IV and were known as Model V.

6.3.3 Model VI

Both the Model IV and the Model V instruments were subject to changes in reading when the instrument was tilted. A large part of this effect was caused by air in the thermopile housing flowing from one side to the other, thus changing the thermal equilibrium of the differential thermopile. The improvements which were indicated in the earlier models were finally incorporated into an instrument known as the Model VI.

The Model VI was built at the request of OSRD for a selective gas analyzer capable of satisfactory operation in a submarine and for other conditions where the instrument would, of necessity, be tilted. A program was started

in May 1944 to build five instruments, redesigned to meet specific requirements for submarines. Three of these instruments were made to have a range of approximately 0 to 8 per cent CO_2 with an accuracy of better than 0.5 per cent. The two remaining devices were essentially the same as the other three except that provision was made for using longer sample tubes. This enabled the sensitivity to be increased by a factor of 2 or 3.

Inasmuch as suitable alternating current is available on submarines, these instruments dispensed with battery operation and were designed for 115 v. This resulted in some simplification of the circuit and the equipment. Insensitivity to tilting effect was secured by evacuating the thermopile and source housings, the internal pressure being reduced to 10 mm of Hg before sealing. The windows were of either LiF or CaF_2, as called for by the particular application. The source was run on regulated 110-v alternating current, and the potential for zero adjustment produced by a thermocouple on the source housing. A simplified amplifier developed by Leeds & Northrop was employed. Although this amplifier did not detect as small a signal as the General Motors amplifier, it was found to be more than adequate for submarine application. This amplifier also operated on 110-v alternating current, and its output was indicated on a zero-to-one milliammeter. For most applications, the only manual

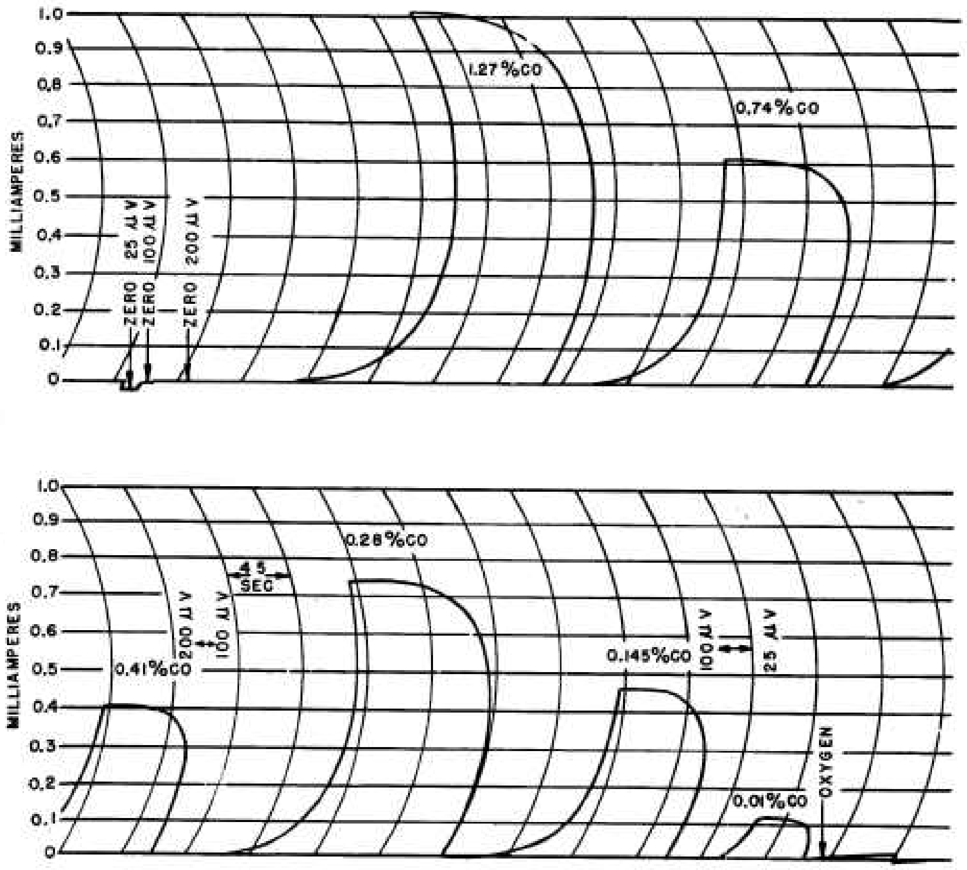


FIGURE 6. Sample of recorder chart, showing the analyses of CO mixtures containing six different concentrations, 0.01-1.27 per cent. The variables recorded are time and milliamperes. The rapidity of sampling and instrument response are indicated. The deflection for 0.01 per cent is sufficient to permit the indieation of 0.005 per cent.

control required was one dial for zero adjustment.

For applications involving low gas concentrations, the voltage regulator did not provide a sufficiently stable voltage source. Also, in some cases a 110-v a-c source was not available. For these reasons, three of the instruments were remodeled so that the source operated from a 6-v battery. This required an additional manual control for the source voltage. The sample tube also was lengthened, a 12-in. tube being used in place of the original 5-in. one. A converter was supplied for the amplifier to produce 110-v alternating current from the 6-v battery. The amplifier, however, could also be operated from a 110-v a-c line if desired.

6.4 APPLICATIONS OF INFRARED DETECTORS AND ANALYZERS[5a]

The most immediate application of the infrared detector was as a measuring device in connection with the design of ventilating systems for tanks. A problem arises because of gases which may be blown back into the tank when gun breeches are opened. The products of combustion of the powder contain important percentages of carbon monoxide, and if this gas gets back into the tank, dangerous concentrations may develop. The gas-analysis apparatus described is particularly well adapted to supply the need for a device which will continuously indicate CO concentrations, as a running sample can be drawn from any desired region in the tank, and changes in CO concentration are quickly evident on the chart. Since this application requires CO measurements down to only about 0.01 per cent, which is readily detected, no temperature shielding is required, and measurements can be carried out in spite of gun concussion.

Another application is to monitor the atmosphere in submarines. In this case, the device is used to indicate or warn of excess CO_2 and is made responsive to relatively large concentrations (up to 5 per cent) by using a short sampling chamber. Tests for CO can also be included. Such tests or routine studies can be made with present apparatus, and it could be incorporated into a relatively simple warning instrument to indicate the approach of dangerous gas conditions automatically.

There is also a definite need for a CO detector in connection with certain ventilating problems in airplanes. To the extent that such problems arise in ground tests or where laboratory-type installations can be made, the present apparatus is satisfactory. However, the more extreme conditions of sensitivity and stability required for a CO warning device (because dangerous concentrations are quite low), together with the extreme temperature and pressure fluctuations, seem to preclude the possibility of developing the infrared detector for a simple CO warning device on airplanes in flight.

Applications of infrared apparatus to the detection of war gases and tests of an apparatus for this purpose at the Edgewood Arsenal indicate that this detector is useful for measuring the so-called *charcoal break* in connection with the determination of the saturation of gas-mask absorbing materials. In such an analysis, air containing the gases to be detected is passed through the absorbing material of the gas mask and then into the analyzing chamber of the gas detector. The charcoal break occurs when the absorbing material becomes saturated for any constituent of the poisonous gas. When this occurs and the constituent begins to pass through the absorber, the fact is immediately indicated by the infrared detector. Since the detector is responsive to any of a wide range of hydrocarbon and other dipole molecules, some of which are almost certain to be present in any poisonous gas which might be considered, gas masks and other protective devices can be tested without the necessity of devising chemical or other means for the detection of the specific gases involved.

Chapter 7

DETECTION OF PLASTIC PARTICLES

7.1 INTRODUCTION AND SUMMARY

THIS REPORT describes experimental work done in attempting to develop a method of detecting nonmetallic fragments which might become embedded in the human body during combat. The plastic used throughout the investigation was Plexiglas. This is the trade name of a polymeric methyl methacrylate resin.

The surgeons of the Ninth Air Force noted that 10 per cent of wounds sustained in combat by the crew members of medium bombers were due to fragments of Plexiglas from shattered windshields and windows. The surgical removal of these Plexiglas particles was slow and difficult because the particles could be found only by probing the wound. X-ray visualization was impossible by standard X-ray techniques because the radiographic opacity of Plexiglas is so similar to that of blood and muscle.

The surgeon's metal locator was useless for Plexiglas or other nonmetallic parts of airplane parts found in combat wounds. Its existence, however, inspired the hope that some similar locator could be developed for Plexiglas.

A summary of reports from Air Force surgeons showed that injuries by Plexiglas were only 4 per cent of casualties in the Eighth Air Force and 10 and 1 per cent of casualties among bomber and fighter crews, respectively, in the Ninth Air Force. Only 3 to 10 per cent of the wounds by Plexiglas were deep, most of the wounds being superficial and presenting no particular difficulty in treatment. Those surgeons who desired a locator for Plexiglas asked that it be sensitive to particles 1 to 2 mm in size.

Three methods of attack were studied extensively. The first of these was the coating of Plexiglas with radioactive materials, the presence of which might be detected with a Geiger-Mueller counter. The second was the development of a low-voltage X-ray technique; and the third was the opacification of Plexiglas. A brief inconclusive study was also made of the X-ray opacification of clothing. The results of these investigations are summarized below.

A radioactive coating containing 10 microcuries of Mn 52 per sq cm permits detection of fragments having more than 1 to 2 sq mm of surface. Among Plexiglas fragments 3 mm and smaller, produced by .50-caliber machine guns or 20-mm high explosive shells, less than one-third of the particles possess as much as 1 sq mm of coated surface. In addition, a lacquer coating on Plexiglas produces optical surface irregularities. It does not appear as if surface coating is a practical solution for detection.

The probability of detecting Plexiglas particles less than 5 mm in diameter in tissue by means of the best low-voltage X-ray technique developed is essentially zero.

When Plexiglas was opacified to X-rays by a sufficient addition of organometallic or organic halogen compounds to be useful, it exhibited marked optical discoloration.

Plexiglas particles, if initially sterile, cause no appreciable irritation of muscle.

Fragments smaller than 3 mm have very little penetrating power, and can be stopped by a layer of light cloth. Those parts of the body which are not adequately protected by hair or regular clothing could be covered by a light garment or hood. Small particles will penetrate deeply into tissue only when the Plexiglas is adherent to a steel fragment.

7.2 ANIMAL EXPERIMENTS

Two sets of experiments with Plexiglas fragments were made with animals. The first set was to determine the amount of damage which might be done to dogs by flying Plexiglas fragments. For this purpose a cubical test chamber, 4 ft on each side, was constructed. The Plexiglas panels, 2 ft by 2 ft by ¼ in., were mounted centrally with respect to one side. One shot was fired at each of three panels with experimental dogs in the chamber to study the penetration and subsequent location of plastic

fragments in animal tissue. High-explosive 20-mm shells were used. The fuzes were very sensitive, and the shells all exploded in contact with the Plexiglas panels.

Three anesthetized dogs were used in these tests, all three being in the chamber at one time. They were laid on their sides, and a patch of the upper side of each was shaved clean to simulate human skin.

A summary of the pathological studies in these three animals is significant because of its bearing on similar injuries which might occur to combat personnel under similar conditions. The wounds varied from tiny abrasions of less than 1 mm to shallow defects in the skin measuring 5 to 15 mm. There were few wider wounds and these were usually associated with particles of steel. No wounds extended more than 1.5 cm below the skin surface. Most involved the skin and subcutaneous tissue. Removal of Plexiglas from the subcutaneous tissue is more difficult than steel because of its marked adherence. This is probably caused by the multifaceted character of the fragments. Very few wounds were present over the unshaved exposed surfaces of the dog's body. Those present were quite large, deep, and contained Plexiglas and steel fused together, as well as large numbers of hairs embedded in the base. Recognition of Plexiglas in the subcutaneous tissue is generally not difficult. The presence of a thick covering of hair is a good, but not complete, protection against Plexiglas injury. When such injuries do take place, they are associated with a considerable amount of crushing and inclusion of many well-embedded loose hairs.

The second group of animal experiments were carried out to determine whether Plexiglas particles which might be left in the body would have any harmful results. For this determination, five mice were anesthetized, and Plexiglas splinters were embedded in the thigh muscles, using sterile precautions. The mice were decapitated after 24, 68, and 120 hours and the thigh muscles studied. In every case, no edema or infection was observed, a healing scar appeared over the injection site, and the muscle appeared normal. The conclusion to be drawn from this set of experiments is that pieces of Plexiglas embedded in muscle produce very mild changes, if any. In support of these observations is the fairly extensive use of this type of plastic as surgical drainage tubes and bone cups in orthoplasty.

The results of these animal experiments indicate that a light covering of cloth or heavy hair affords good protection from injury due to flying Plexiglas particles. Injury by the fragments, except where they are associated with pieces of steel, is never deep but usually results in abrasions to the skin and the immediately underlying subcutaneous tissues. Fragments of Plexiglas remaining in the body tissues cause only very mild inflammatory changes, or none at all.

7.3 DETECTION BY RADIOACTIVITY

Plexiglas shatters under the impact of antiaircraft shrapnel, explosive shells, and machine-gun bullets. The feasibility of coating the Plexiglas surface with a detectable coating was extensively studied. The usefulness of this type of detection depends on the size of particle to be detected. To meet the desired military requirements of detecting particles in the range from 1 to 2 mm or less, the results of these studies indicate that no surface coating would be practical. This conclusion is drawn from two series of tests, one with .50-caliber machine-gun bullets, and one with high-explosive 20-mm shells. The amount of surface carried by the Plexiglas fragments was studied by coating the inner surface with a radioactive coating, and testing the fragments for activity to obtain a result of the presence or absence of a detectable amount of surface. For the .50-caliber machine-gun bullets, less than 20 per cent of the particles in the size range from 1 to 2 mm showed any detectable surface; for the 20-mm cannon shells, about 6 per cent could be detected. From these tests, it is apparent that coating the inner surface of all Plexiglas in aircraft will not solve the problem of locating plastic fragments in wounds. A large fraction of the smaller fragments, which are the most difficult to locate by standard surgical techniques, do not carry a detectable amount of inner surface.

7.4 DETECTION BY LOW-VOLTAGE X-RAYS

The most extensive experimental work was done in an attempt to evaluate the use of low-voltage X-rays in the detection of Plexiglas particles. To determine the conditions under which Plexiglas could be detected in the human body, use was made of a blood phantom. This consisted of a copper tank with a 1/32-in. bakelite bottom. The tank was filled to various depths with whole blood from normal adults. Particles of shattered Plexiglas, which were screened in millimeter steps in known numbers, were sprinkled at random on the bottom of the tank.

In the initial part of the investigation, use was made of a step wedge of Plexiglas with 1/32-in. steps. During the part of the experiment in which the thin wedge was used in the phantom, the position of the wedge from the bottom of the tank was varied over wide limits. It was concluded that in every case contrast was very much more important than definition for the detection of the Plexiglas in blood. In the case of the shattered particles, the definition was a maximum since the particles rested on the bottom of the tank.

The procedure of setting up criteria for optimum detection under varying conditions was as follows: (1) screened particles of Plexiglas having known sizes were radiographed through varying depths of blood at various voltages; (2) radiographs of the phantom were always taken of 100 particles; (3) the number of particles recognized as Plexiglas particles on the radiograph were counted by a highly trained roentgenologist. This determined the per cent recognition, which was used as a test of optimum technique, which field observation would parallel.

It was found, as a result of this experiment, that the lower the voltage used, the better the contrast between the Plexiglas particles and the blood. One is limited by the time of exposure in the possible softness of the useful radiation. Since the exposure time increases with the square of the decrease in voltage, a certain rather critical voltage exists, below which the exposure time becomes unreasonably long. This critical voltage obviously depends on the thickness of material which the X-ray beam must penetrate. A family of curves is shown in Figure 1, in which exposures in milliampere-seconds are plotted as a function of peak voltage for a number of different blood

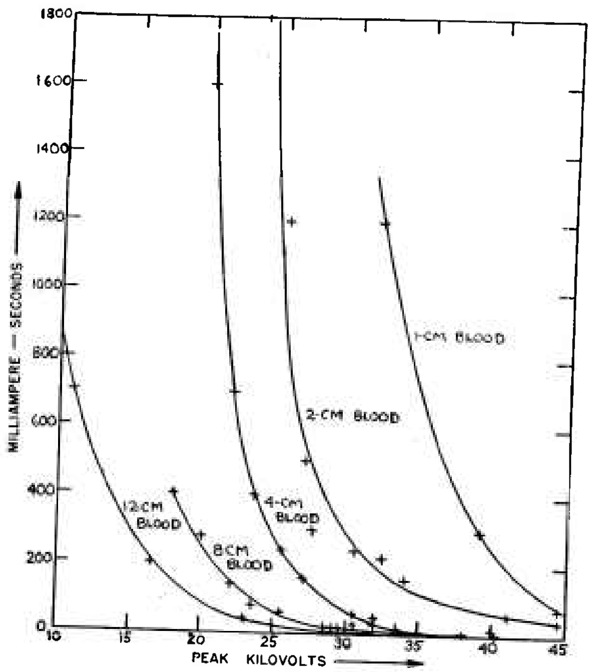


FIGURE 1. Exposures in milliampere-seconds as a function of peak voltage for a number of different blood thicknesses for a radiographic density convenient for a standard diagnostic interpretation.

thicknesses. These curves are all for the same radiographic density, chosen as convenient for standard diagnostic interpretation.

One of the interesting findings of the investigation was the fact that an optimum film density exists. As the films become more dense, the per cent detection of the Plexiglas particles increases up to a broad maximum corresponding to a film density of about four, and thereafter the per cent recognition decreases with increasing density. A plot of this result is shown in Figure 2, where a plot is made of the per cent recognition as a function of the exposure.

The per cent recognition as a function of peak kilovolts for a number of different size Plexiglas particles in a fixed depth of blood at optimum density is shown in Figure 3. In

Figure 4 a plot is made of the per cent recognition as a function of voltage for a fixed size of Plexiglas particle for a number of different blood levels.

Experimental patch tests were carried out and showed no erythema reaction to an expo-

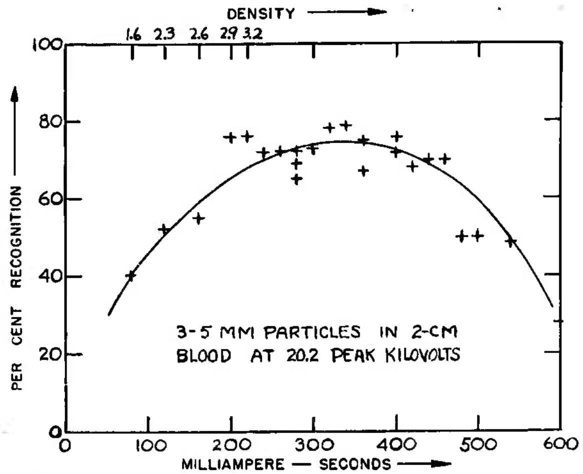


FIGURE 2. Per cent recognition as a function of film density or milliampere-second exposure.

sure of 720 ma-sec at 32 in. and 20.2 kv with a field size of 11 sq cm on the flexor surface of the forearm, using a fair-skinned individual. The number of roentgens delivered to the skin during this exposure was measured as 14. Since

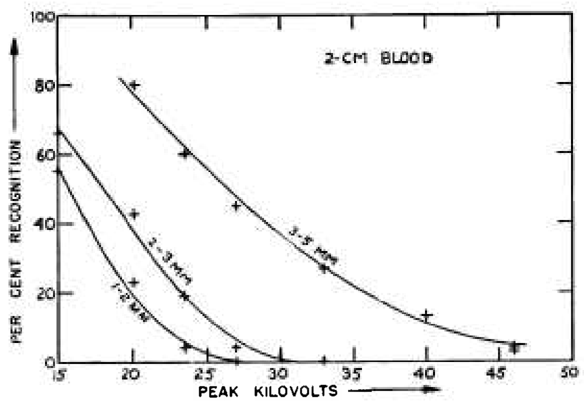


FIGURE 3. Per cent recognition as a function of peak voltage where a number of different size Plexiglas particles are in a fixed depth of blood at optimum density.

this exposure was far greater than that used in the radiographic tests, it was concluded that the exposures were limited rather by the conditions of immobility than erythema.

As a result of studying a number of different commercially available types of film, it was found that Eastman No-Screen film gave the optimum contrast. This film is slower than the usual film used in medical radiography (Eastman Blue-Brand), but the gain in contrast was so marked in No-Screen over Blue-Brand, that the former is always to be recommended in this type of radiology.

The fogging of the film due to backscattered radiation was remarkable in this low-voltage X-ray work. At 20 kv it was found experimentally that about half the density of a film backed with air, paper, or wood was due to

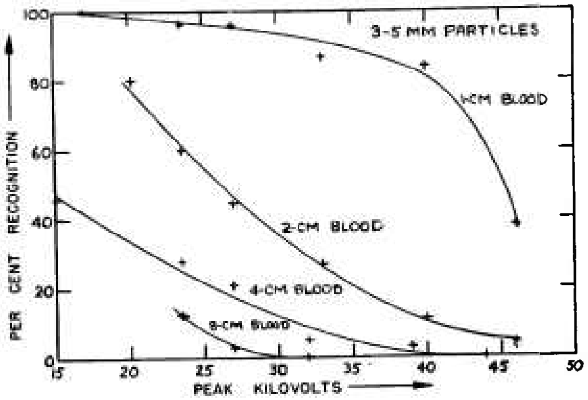


FIGURE 4. Per cent recognition as a function of peak voltage for a fixed size of Plexiglas particle for a number of different blood levels.

backscattered radiation. This backscattered radiation, since it blackens the film without giving a radiographic image of the Plexiglas, does no good whatever, and serves only to obscure the image of the Plexiglas particles. Radiographs in this investigation were always taken with the film intimately in contact with a lead backing $1/8$ in. thick.

An experimental tissue sample was prepared by removing one of the legs of the dogs which had been used in the experimental studies of Plexiglas fragments from explosive shells. Pieces of Plexiglas were embedded at different depths in the leg. The difficulty of detecting Plexiglas fragments in the inhomogeneous media of layers of muscle, fat, and other tissues was illustrated by radiographs of the

dog's leg. The Plexiglas is rendered very difficult to detect when confused with soft tissue radiographic detail. The work with the homogeneous phantom indicates the direction in which contrast can be improved, but the detection in homogeneous media will be much more probable than in the inhomogeneous medium of living tissue.

A summary of the radiographic tests is as follows: contrast is the most important factor in detecting small particles of Plexiglas—the lower the voltage, the higher the contrast. For each given thickness of attenuating medium there is a minimum practical voltage determined by the maximum practical exposure. There is an optimum density for maximum probability of detection, requiring a carefully controlled technique. Optimum results were obtained with the use of Eastman No-Screen film backed by 1/8-in. sheet lead. The range of recommended exposures was found to be below erythema threshold. The probability of detecting Plexiglas particles in heterogeneous media is necessarily lower than in homogeneous media. The corresponding probabilities of detection of Plexiglas particles in the heterogeneous radiographic media of human tissue will be lower. This effect is such that the probability of detecting particles below 5 mm in diameter in tissue is essentially zero.

7.5 DETECTION BY X-RAY OPACIFICATION

One of the methods available for rendering Plexiglas radiologically detectable is by incorporating material of greater density into the methyl methacrylate sheeting. This possibility was investigated by preparing four samples differing in degree of transparency to X-rays. Information was not available as to what specific materials had been added other than that they were organometallic and organic compounds. The one sample which was untreated showed no color. The other three samples showed distinct yellow coloration. Spectral photometric studies of these samples showed that absorption in the blue was very marked. In the case of the most heavily treated sample, transmission at the violet end of the spectrum was less by 20 per cent than in the case of the untreated sample, and less by 5 per cent in the red. No information was available on possible changes in structural properties such as moldability of Plexiglas due to the opacification.

Changing of the X-ray transparency of Plexiglas must be done with care since the density of Plexiglas for X-rays is originally less than that of blood. If the opacity of Plexiglas is not increased enough, there will be less contrast than there was originally.

Chapter 8

LOCATING UNEXPLODED BOMBS

By *F. L. Yost*[a]

8.1 INTRODUCTION[b]

The specifications for a satisfactory bomb-locating instrument were as follows:

1. The instrument must be capable of locating buried bombs under the following conditions:

Weight of bomb	Approximate dimensions	Distance under surface
100 lb	8-in. diam, 30 in. long	15 ft
500 lb	15-in. diam, 48 in. long	20 ft
1,000 lb	19-in. diam, 54 in. long	25 ft

These limits must be attainable, even though the bomb is in the vicinity of other buried objects, magnetic or otherwise, such as water pipes.

2. The instrument must be capable of locating in three dimensions a buried bomb to the following accuracy: horizontal direction, ±1 ft; vertical direction, ±1 ft.

3. If the instrument is not capable of locating a buried bomb from the surface because of interference from buried objects, and if it becomes necessary to resort to the use of a bore-hole search coil, the design of the coil should be such that it can be used in a hole not over 6 in. in diameter (preferably smaller) and that it has a working range of at least 10 ft.

4. It is desirable that not more than one hour should elapse from the time the instrument is placed in operation until the bomb is located.

5. The equipment must be portable so that it can be operated at any site.

6. The unit must operate without dependence on commercial power lines; the power required for operation must be small enough to be supplied by self-contained batteries or a portable gasoline-generator set.

7. The equipment must be reasonably simple to operate and should be such that an average individual without technical training may learn to use it effectively after brief instruction.

8. The equipment must not be extremely delicate. It should be at least as sturdy as ordinary radio equipment, so that average handling during transportation will not cause damage or put it out of adjustment.

9. The design should be such that laboratory facilities are not necessary for making adjustments. Reference standards, if needed, should be self-contained.

10. Any indicators should be visual rather than audible.

8.2 SUMMARY OF DEVELOPMENT

Work on this project was done by the Kannenstine Laboratories. A number of different methods of locating bombs were studied.[1-9] The most promising seemed to be magnetic locating methods. As a result, practically all the work on this project was in that direction.

Preliminary investigations indicated that if the magnetic anomaly in the vertical component of the magnetic intensity resulting from the presence of an unexploded bomb was to be used to detect it, a magnetic gradiometer (which measures the gradient of the magnetic intensity) would be more suitable than a magnetometer (which measures the magnetic intensity). Two types of *vertical-vertical gradiometer* [VVG] were built for use at ground surface to determine the difference in vertical magnetic intensity at two different positions on a vertical line (i.e., to measure the vertical gradient of the vertical component of the magnetic intensity). Later a *vertical-horizontal gradiometer* [VHG] was developed and designed for use in bore holes to determine the difference in horizontal component of the magnetic intensity at the different positions on a vertical line (i.e., to measure the vertical gradient of the horizontal component of the

[a] Technical Aide, Division 17, NDRC.

[b] The control number for this project was OD-63.

magnetic intensity). It was believed that this latter type of gradiometer would be more effective in locating the position of a bomb.

The VVG's devised for use at ground surface did not fulfill requirements 1 and 2. In fact, further development would have been required to produce a satisfactory surface detector, even if tests with the experimental models had not indicated that the presence of extraneous magnetic objects in the ground would make the usefulness of such a device quite limited.[6, 8] Accordingly, work was done on a VHG for use in a bore hole.[9] Although this instrument apparently met requirements 3, 5, 6, and 10, it probably would not have met requirement 4. It was merely a promising experimental model; hence no statement can be made as to whether requirements 7, 8, and 9 were met.

The essentially inconclusive results of this project were in part caused by the fact that during work on it the problem of locating unexploded bombs decreased in importance. The press of work on more important projects resulted in termination of this contract with very little testing of the experimental models, and without following lines of investigation suggested by the tests which were run. For the purpose of recording the work done on the project should the problem become important again, this report discusses the bore-hole gradiometer and, in Section 8.4, the other less promising detection methods.

8.3 DESCRIPTION AND TECHNICAL INFORMATION

The VHG[9] for use in bore holes for locating unexploded bombs is the result of an extension of work done on two designs of VVG (for locating unexploded bombs by measurements made at ground surface), which will be discussed later. Given any direction in the horizontal plane, the purpose of the VHG is to determine whether the magnetic fields in that direction differ at two different specified points along a vertical line, and, if so, to study the variation. As shown in Figure 1, the VHG consists of a pickup unit, which is to be lowered into a bore hole, and an indicating unit.

The construction of the pickup unit is shown diagrammatically in Figure 2. The gradient-sensitive element consists of two narrow coils connected in series and supported, one above the other, by a comparatively long straight wire to the center of which is attached a mirror. This assembly is supported vertically by taut

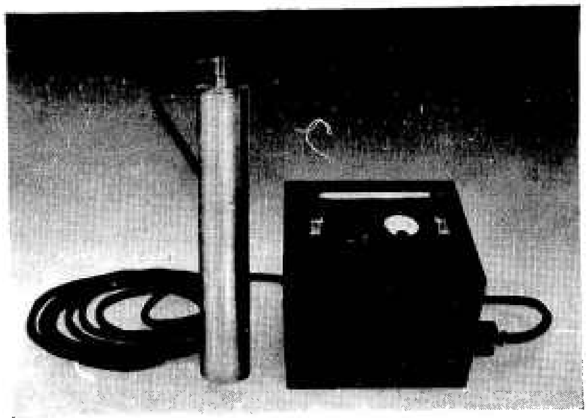


FIGURE 1. Pickup unit and indicating unit which make up the VHG.

suspensions, which also serve as electric connections to the respective coils. The coils are so connected that the torque on one is opposite to that on the other when the system is in a uniform field and current is fed to the coils.

The system can be adjusted to give zero oscillation of the mirror when it is fed by alternating current in a uniform magnetic field (i.e., one in which the field components at both coils and in their plane are the same, irrespective of orientation of the coils). Maximum sensitivity in such adjustment is attained by use of an alternating current, the frequency of which is equal to that of the fundamental mode of vibration of the system. If this system is so driven in a field in which the horizontal components at the two coils and in their plane are different, the result is an oscillation of the mirror with an amplitude proportional to the driving current and the difference in the two horizontal components. In other words, the amplitude of oscillation is proportional to the product of the driving current and the vertical gradient of the horizontal field component in the plane of the coils.

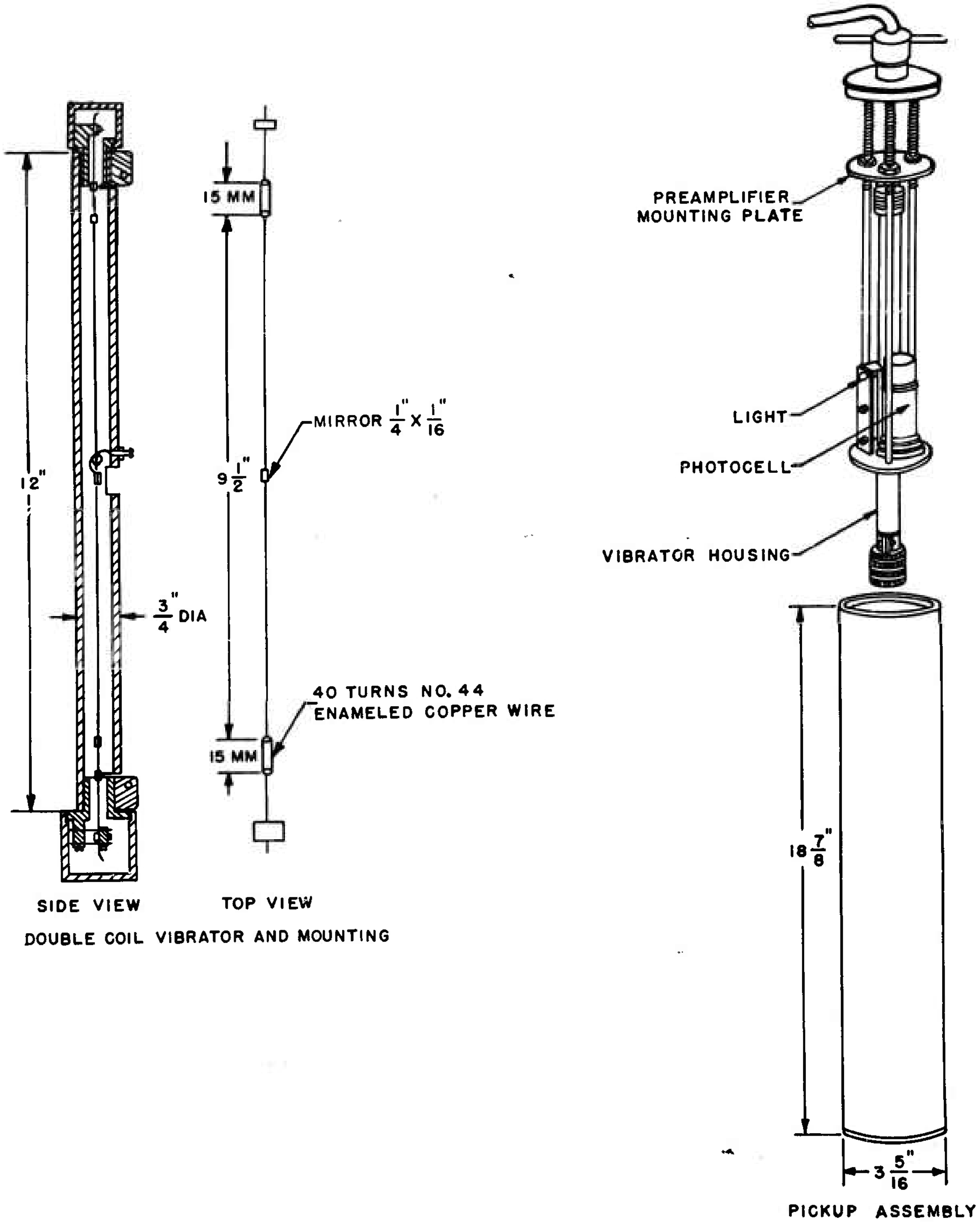


FIGURE 2. VHG pickup.

The displacement of the mirror is converted into a voltage by means of a light source and photocell. This voltage is amplified and drives the vibrator (i.e., the mirror and coil system). The system is designed to constitute a feedback oscillator when the vibrator is oriented in a magnetic field having a sufficiently high gradient. The amplifier is provided with a delayed automatic gain control operating on the grid bias of one tube. A meter in the plate-supply circuit of this same tube serves as an indicator of gain.

The indicating part of the gradiometer which remains at the surface contains all batteries and the whole amplifier, except a one-stage preamplifier which follows the photocell. It weighs 27 lb complete. The pickup weighs 10.5 lb with the 25-ft connecting cable but without lowering rods.

For the system to oscillate in a uniform external field, an internal gradient field, fixed with respect to the sensitive element, is provided by a small permanent magnet. It should be weak enough to require the use of the highest usable amplifier gain for oscillation.

When the system has been properly adjusted, the gain (i.e., the automatically controlled amplification applied to the voltage resulting from the oscillation of the system) required to maintain oscillation is independent of instrument orientation in a uniform field; hence the meter reading, which indicates the gain, is independent of the orientation. If the instrument is in a magnetic field which has a detectable vertical gradient of the horizontal component, the meter reading (i.e., the gain) varies with orientation in the field. The meter reading will be a minimum when the instrument is so oriented that the external and effective internal gradients are parallel; and it will be a maximum when the external and internal gradients are antiparallel. Comparison of meter readings at different orientations serves to determine the magnitude and approximate direction of the external gradient.

Although the scale is not actually linear, a rough determination of the sensitivity of the device indicates that it is about 10 gammas per ft per 0.01 ma. Tests were made outdoors above ground with a vertical pipe 79 in. long and 5.5 in. in diameter as the test object. Readings were with the pickup at about the height of the center of the test object and 7 ft west of it. The average difference in WE readings with and without the object was 0.12 ma; for NS readings, 0.02 ma (of the order of the average deviations). Computation of the direction of the object by use of these data would result in an error of about 10 degrees ($\tan^{-1} 2/12$). The worst pairing of single sets of data would give an error of about 27 degrees. On a subsequent test the direction calculated from the average data was in error about 15 degrees.

The operation of the VHG is slower than that desired, as the time between steady readings is about one minute. In actual use a descent in the bore hole would be made at a fixed orientation, with readings being taken at intervals. If no significant anomaly appeared, an ascent would be made at an orientation 90 degrees from the first. If this showed no significant anomaly, it would be concluded that the bore hole was not close enough to the bomb for the instrument to indicate its location. If an anomaly were found, readings at the depth of its maximum value would be taken in different orientations to determine the direction of the gradient. The bomb depth would be approximately that of maximum anomaly, and the distance of the bomb from the bore hole could be estimated from the shape of the anomaly-depth curve.

It can be said merely that a first model of a satisfactorily portable VHG suitable for locating buried iron-case bombs by measurements in bore holes of 4-in. diameter was developed. Its speed of operation does not meet requirements. It apparently has enough sensitivity to permit the location of a large bomb from a bore hole passing within 7 to 10 ft of it. However, it was not possible to make tests in actual bore holes or to attempt certain improvements of the instrument by elimination of difficulties discovered in preliminary testing before the date set for termination of the contract. The instrument is best described as a promising experimental model. If the problem of locating unexploded bombs again becomes important, it is conceivable that this instrument could be developed into a form suitable

for field use, and that it would successfully accomplish its purpose.

8.4 HISTORY

The first attempt at magnetic location was directed toward the development of the VVG's. The first model had several disadvantages, but was sufficiently promising to justify work on a second one in which the disadvantages of the first were eliminated as much as possible.

The field-sensitive element in both gradiometers is a vibrating coil, or vibrator, similar in construction to a taut-suspension-oscillograph galvanometer. As shown in Figure 3, the coil is horizontal and centered between two coaxial Helmholtz coils whose axes are vertical.

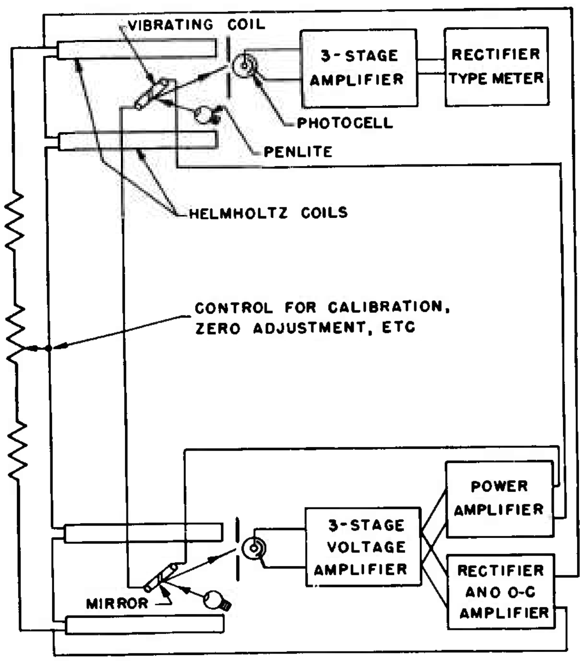


FIGURE 3. Diagrammatic sketch of VVG.

To measure the vertical gradient, two of these coils are used, one vertically above the other.

In the first gradiometer, photocells were employed to observe the vibrations of the coils. The lower of these was coupled to an amplifier driving the vibrators, and also to a current-control circuit automatically reducing the magnitude of the lower Helmholtz field almost to that of the vertical component of the earth's field, which it opposes. The residual field is just strong enough to permit the lower system to function as an oscillator. The upper Helmholtz coils were connected in series with the lower, so that the upper field was approximately equal to the lower external field except for an additive constant, and the total upper field was then the difference between upper and lower external fields except for an additive constant. The vibration of the upper moving coil served to measure this field; and knowledge of this field and the separation of the coils determined the gradient. This instrument had a precision of about 0.5 gamma per ft, but with further development higher precision could have been expected.

Tests indicated moderate success in detecting buried magnetic objects simulating bombs, but revealed a number of disadvantages. A new VVG was designed to remove these difficulties.

In the new system, each vibrator with its associated photocells and amplifier constitutes an oscillator driving the vibrator at its own resonant frequency. The essential feature of this second system is that the upper oscillator system controls not only its own Helmholtz-coil current, but also nearly all the lower Helmholtz-coil current. The lower oscillator system controls only the small fraction of lower Helmholtz-coil current required to adjust for the difference in vertical field between the upper and lower systems. This part of the lower Helmholtz-coil current may be made a small fraction of the lower control current, which is measured by the meter, by means of a simple resistance network. Thus, a relatively insensitive meter, in this case a 0-1 milliammeter, can be used to measure a change in lower Helmholtz-coil current which is a small fraction of the meter reading. It is a system superior to the first gradiometer.

This and various other changes in design were more or less successful in removing difficulties. While the new gradiometer sometimes performed satisfactorily, there were frequent jumps in zero and, occasionally, extreme unsteadiness in indication, the causes of which

were not determined. However, it was believed that an instrument of this type could be made to operate satisfactorily.

In addition to the magnetic methods described, the following possible locating methods were considered and studied: (1) electrical methods—r-f and potential-drop ratio, (2) thermal methods, and (3) seismic methods.

The r-f electrical methods similar to those used in anti-tank mine locators (e.g., a large exploring coil which is the inductance element of a vacuum-tube oscillator) did not appear to be promising, as they are inherently short-range methods and particularly affected by water pipes and other interfering material. Also, there seemed to be little value in another method in which a fixed transmitting antenna was used to produce a field in the vicinity of the conductor, and a portable directional receiver was used to determine the direction of the minimum signal at various points. Large effects were produced by extended conductors such as water pipes, and no observable effects by compact conductors such as bombs.

Conductivity measurements—the basis of the potential-drop-ratio method[3]—were not successful. Water pipes and other extraneous materials produced large anomalies, and small objects such as bombs produced no observable effects.

Thermal methods were investigated theoretically.[4] It was concluded that they would have very little application, if any. Observable temperature change would occur only after the lapse of a long time and only at short distances from the bomb. There were also practical objections, such as the difficulty of putting a thermometer in the earth without raising its temperature. There is a slight possibility of locating the path of the bomb by the temperature rise, but this is of doubtful value.

The use of seismic methods, utilizing waves which are refracted or reflected by the bomb, was not adequately tested by experiment, but it was believed to be impractical. Theoretically, the wavelength to be used should be short (probably about equal to the diameter of the bomb). Attenuation at such a wavelength is great, making it doubtful that sufficient energy could be sent to the bomb and reflected to the surface for observation, unless the source was extremely powerful.

Chapter 9

DEVELOPMENT OF AN ELECTROMAGNETIC MASS DETECTING SECURITY DEVICE

By *F. L. Yost*[a]

9.1 INTRODUCTION

THIS PROJECT resulted from a request of the U. S. Secret Service for a device which would indicate the approach of metallic objects, such as concealed weapons.

9.2 REQUIREMENTS

The apparatus was to detect metallic weapons, particularly pistols, concealed on a person passing through a constricted passageway, e.g., a doorway 4 ft wide by 7 ft high. The detection was to be made without the knowledge of the person under surveillance. Some of the existing devices for such a purpose had harmful effects on watches; others were difficult to conceal; and most of them failed to provide satisfactory discrimination between weapons and common metal objects of small size. It was desired that these difficulties be corrected and that the final apparatus be such that it could be operated by personnel with a minimum of training.

The requirements were not made more specific because it was not known how much could be done in the way of distinguishing between a concealed metallic weapon and a legitimate object such as a cigarette lighter or a tobacco can. Therefore, the project was originally exploratory in nature; after it became evident that some degree of success could be achieved in the problem, work was devoted to improving the most promising method.

9.3 SUMMARY OF DEVELOPMENT

An attempt was first made to develop an instrument which would detect metallic objects by their magnetic effects.[1] The difficulties of discrimination in this method seemed insurmountable. It was, therefore, discarded in favor of a method in which metallic objects were to be detected by their disturbance of the flux density of an alternating electromagnetic field through which they passed.[2-5]

It was found that the proper choice of field frequency assisted in discrimination of the type of metallic object detected. In addition, a thorough study was made of other factors which influence discrimination, and attention was given to improving sensitivity and to reducing effects from extraneous alternating fields (particularly 60 c).

In the final development, the apparatus indicated the sizes of guns quite satisfactorily. There was some overlap between the smallest guns and pocket tobacco cans. Cases for glasses were found to be about as effective as .25-caliber automatics. It was also found that officers' caps with steel bands have a strong effect. However, no other articles were found to give misleading indications; pocket knives and keys barely registered. In spite of the minor discrimination difficulty still remaining, the U. S. Secret Service was satisfied with the development.

As finally installed for operation, the unit proved satisfactory except for disturbance suffered from moving metal parts which had not been removed, as planned, from the doorway in which it was placed, and a high level of interference from air-conditioning apparatus located near-by. This interference seriously hampers the use of the apparatus, but the field coil can be enlarged and its field increased sufficiently to override the interference.

9.4 DESCRIPTION AND TECHNICAL INFORMATION

In general, a device which will indicate the presence of an iron or steel object that passes

[a] Technical Aide, Division 17, NDRC.

through an alternating electromagnetic field must depend for its operation on some disturbance of that field. This may be accomplished in several ways, such as (1) by a disturbance of the flux density of the field, (2) by a phase shift between two points in the field, (3) by a change in the mutual inductance between two or more coils in the field, or (4) by a change in either the inductance or the Q of a coil in the field. Tests were made on all the methods mentioned. It was found that the one giving the most positive indication with the least amount of equipment required, and generally best suited to the purpose described, was the flux-density-disturbance method, of which the mutual inductance method is a special case of practical value.

Figures 1, 2, and 3 illustrate the general idea of the method[2] (although the final number and arrangement of coils were not exactly as shown in Figures 1 and 2). As shown in Figure 1, a field coil which sets up an alternating electromagnetic field is so arranged that its axis passes through the mid-point of a small pickup coil, the axes of the two coils being perpendicular to each other.

Figure 2 shows the coils of Figure 1, viewed from directly above. This figure shows two possible sets of magnetic-flux lines set up by the field coil. The dotted lines represent a series of undistorted flux lines, while the dashed ones represent a distorted series. Complementary lines are marked 1 and 1′, 2 and 2′, etc. The normal, undistorted flux lines are more or less perfectly symmetrical about the field-coil axis. Thus, for each line passing to the left of the pickup coil, a complementary line passes to the right. Accordingly, the pickup coil has zero voltage induced in it from the field coil if it is set in the position shown. The dashed lines represent the magnetic-flux lines when distorted by the presence of a flux-distorting object. They correspond roughly to those representing the undistorted field pattern, but they are shifted in position. Because of the field distortion, the pickup coil is no longer balanced with respect to the field coil, and some voltage is induced in it. The amount of induced voltage depends on several factors, such as (1) the amount of distortion of the flux pattern which would be affected by the mass, shape, electric conductivity, magnetic permeability of the distorting object, and the position where introduced into the field, (2) the strength of the electromagnetic field at the pickup coil, (3) the core material, (4) the length of the core, and (5) the number of turns on the pickup coil.

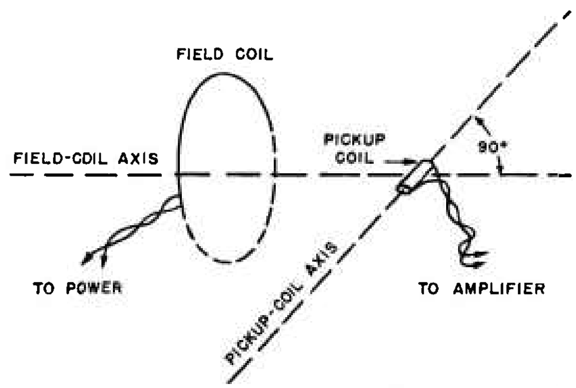


FIGURE 1. General arrangement of field coil and pickup coil.

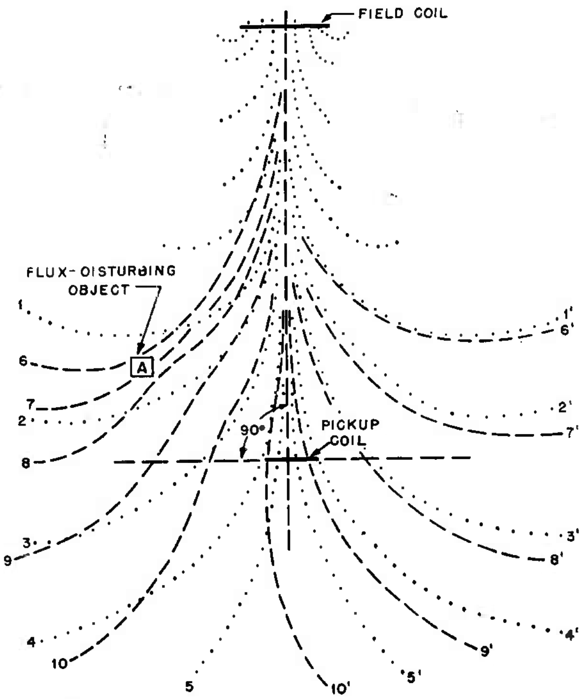


FIGURE 2. Effect of a flux-disturbing object on the electromagnetic field between field coil and pickup coil.

The distorted field resulting from the presence of the flux-distorting object may be de-

scribed in two ways: it may be said that the original field is warped by the object; or it may be said that the exciting field is still in its original form, but that a new or secondary field is added to it by each disturbing object. By either method the same result is achieved, because the primary field plus the secondary field is equivalent to the warped field. The secondary components of fields for various objects may have different directions at a given point because the disturbing objects are in various positions; and the phases of the components differ with the electric properties of the objects. Copper and iron, for example, cause effects nearly 180 degrees apart in phase, and therefore practically opposite in effect.

For an undistorted field, Figure 3 shows how the induced voltage varies when the pickup coil is rotated to make its axis approach coincidence with that of the field coil. Theoretically, the induced voltage reaches a maximum when the axis of the pickup coil coincides with that of the field coil; actually, the amplifier which would be associated with the pickup coil would overload long before any such degree of rotation would be reached, so that Figure 3 illustrates the effect of only a small amount of rotation.

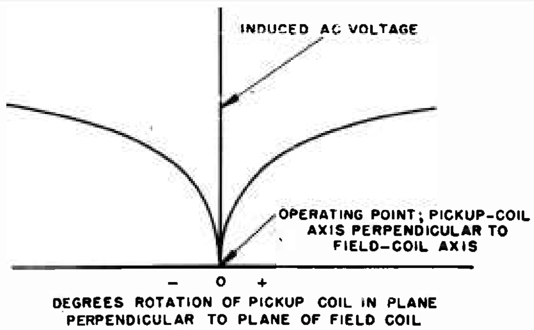


FIGURE 3. Induced voltage as a function of degrees of rotation of pickup coil in plane perpendicular to plane of field coil.

The maximum detecting effect is obtained if the system operates at the null point, which is at the cusp of the curve. In practice the pickup coil responds not only to the direct field-coil component and the secondary component of the object being detected, but also to other unchanging components which cannot be cancelled against one another because of difference in phase, direction, and strength. Accordingly, as explained later, it is necessary to introduce a buckout voltage in the pickup coil to obtain the null point electrically.

The induced voltage in the pickup coil does not depend on the rate of motion of the metallic object, but rather on its *position* relative to the two coils. When a flux-distorting object is passed between the field coil and the pickup coil in a direction parallel to the core of the pickup coil, there will be an induced voltage as the object approaches the coils. The voltage will reach a maximum in one direction when the object is in such a position relative to the two coils during its approach as to produce the greatest amount of flux distortion. As the object is passed between the two coils, the induced voltage drops, passing through the zero value, and then rises to a maximum in the opposite direction when the object is in such a position that it produces the greatest flux distortion on the other side of the pickup coil. As the object continues its motion, the induced voltage returns to its normal operating value.

In the final arrangement, two pickup coils were used, neither on the axis of the field coil. The arrangement of the coils and the associated apparatus is as shown in Figure 4. The complete problem resolved itself into a number of subproblems: the determination of a suitable field frequency and the designing of a satisfactory oscillator and associated field coil which

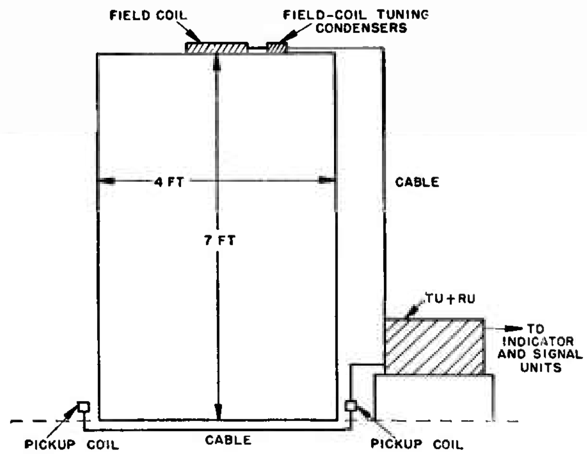


FIGURE 4. Arrangement of coils and associated apparatus in a door frame.

would be moderate in size but would set up a fairly strong field; the designing of pickup coils, together with suitable arrangements for obtaining null points; and the designing of an amplifier which would give sufficient sensitivity with the existing field, and which at the same time would not be affected by extraneous or transient fields.

Preliminary tests[2] in the frequency range from 1,000 to 10,000 c showed that an object made of nonferrous material, such as copper, aluminum, or brass, produced distortion of the electromagnetic field ranging from slight amounts at 1,000 c to approximately 50 per cent of that produced by a small tobacco tin at 10,000 c. As it was undesirable to have nonferrous articles produce indications, a frequency below 1,000 c was indicated. A frequency as low as 60 c was undesirable, because work with that frequency had shown that there were serious interference effects. Accordingly, a field frequency of 500 c was decided upon, that particular value being chosen because it was thought at the time that a commercial alternator might be used. (It was later decided to build an oscillator-amplifier.)

Work on an oscillator-amplifier passed through a series of phases and trials[3] until an oscillator-amplifier and associated field coil were developed which were sufficiently powerful to set up the strongest electromagnetic field required. The final circuit design[5] is shown in the *transmitter unit* [TU] in Figure 5. It has a power rectifier, using a 5U4-G tube in a conventional circuit. In addition to high voltage for the 6L6 power amplifiers, a stabilized lower voltage is provided for the 6SN7 oscillator. Two VR-150-30 gas tubes control the voltage roughly. The 6J5 tube which follows is a surge suppressor which irons out minor jumps of voltage that may occur in the VR-150-30 gas-tube regulators.

The 6SN7 oscillator drives push-pull 6L6 tubes, which deliver their output to the field coil. The field coil is a push-pull tuned coil connected directly in the plate circuit and designed to suit the tube impedance. Because of tuning, the circulating current in the field coil is much heavier than the plate current of the tubes. The field strength measured at the center of the field coil is 21.8 gauss; and the power dissipated in it is about 23 watts.

It was originally planned to use Mu-metal cores in the pickup coils, but some concern was felt as to the relative ease with which such cores could be saturated by interfering fields. Tests showed there was not much probability of such a difficulty arising; but, to avoid the possibility of trouble, high-impedance audio-transformer windings were used as air-core coils. A pickup coil is fastened on each side of the door, 2 to 3 in. above the threshold and concealed by the door frame. Some allowance is made for longitudinal, horizontal, and vertical adjustment and rotation of the coil.

As mentioned above, it proved impracticable to obtain null points for the pickup coils solely by their adjustment relative to the field coil. It was, therefore, decided to adjust the coils for a moderately good balance and to complete the null by bucking the residual voltage out electrically with a component of controllable phase and amplitude. The circuit which furnishes the buckout voltage is shown in the TU in Figure 5. The phase is adjusted by means of two phase-shifting networks in cascade. Each network provides a range greater than 90 degrees, giving a total of over 180 degrees. The amplitude range is controlled by a single potentiometer of 0.2 megohm, wire wound.

There is another voltage injected into the *receiver unit* [RU] (see Figure 5) from the TU, the sensitizing or control frequency, which will be discussed later. This voltage is adjusted roughly in phase by means of the "control-frequency-phaser" tap switch. It is merely set on the position that gives the largest deflection when a sample gun is carried through the doorway.

The development of a receiving amplifier was beset with considerable difficulty in eliminating interference. At first a selective amplifier built on the heterodyne principle was tried, with two resistance-coupled stages to discriminate against 60-c pickup. There was too much interference from 60 c and harmonics produced by small motors and transformers near the pickup coils. Filters to remove 60-c interference and low harmonics were tried, but higher harmonics were found to be of sufficient importance to

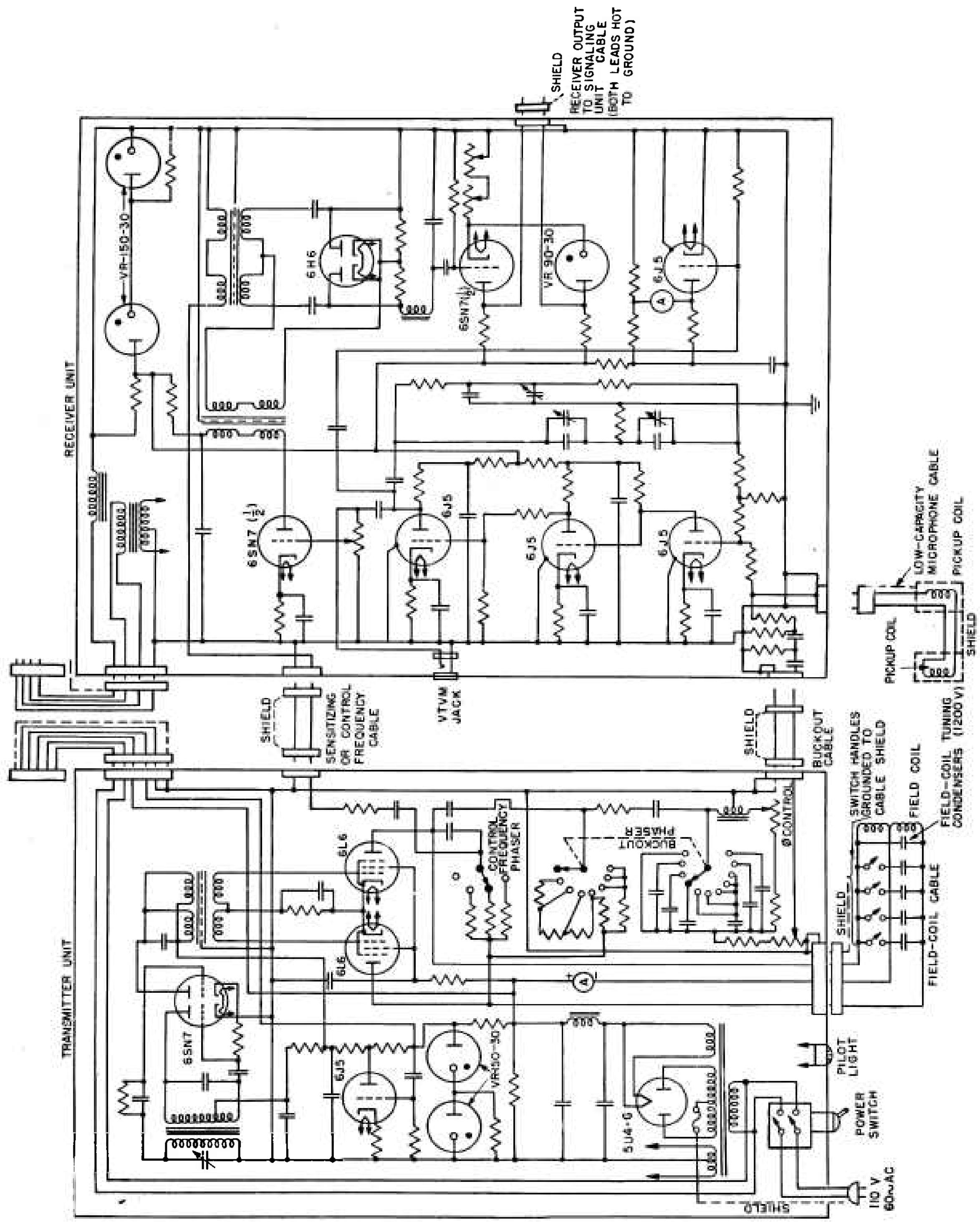


FIGURE 5. Wiring diagram for TU and RU.

make this method impossible. Finally the RU illustrated in Figure 5 was developed.

In the RU the signal path starts at the lower left corner of the diagram and follows clockwise around it. The input to the first 6J5 tube includes the signal from the pickup coils and the buckout voltage which enters through a high-pass filter. The first three 6J5 tubes are used as a resistance-capacitance tuned, inverse feedback amplifier that is highly selective to the 500-c signal. (The amplifier bandwidth is about 5 c.) This is followed by the 6SN7 amplifier stage and the 6H6 diode discriminator. The discriminator is sensitized or controlled by frequency from the power oscillator so that it is highly selective to the desired phase and frequency. (The discriminator bandwidth is about ¼ c.) The use of extreme selectivity does not demand equivalent stability of the 500-c oscillator and discriminator, since the discriminator response inherently follows any drift of the oscillator frequency.

The resulting d-c output fluctuations pass through the 4,000-henry choke into a 0.25-μf condenser, to eliminate interfering kicks of very short duration. The following condenser of 0.5 μf and resistor of 2 megohms eliminate any slow drifts due to temperature changes or other causes.

The second 6SN7 stage drives the recorder. It is connected bridgewise with two resistors and a VR-90-30 gas tube. The recorder current depends on the difference between the fixed gas-tube voltage and the variable plate voltage of the 6SN7.

The 6J5 tube in the lower right corner of the diagram serves as a sort of logarithmic voltmeter. Its grid is excited by the signal in the amplifier, and its plate-current variations are indicated by the 0-200 microammeter. The meter reads about 170 or 180 for zero a-c input, which occurs when the buckout controls are perfectly adjusted. The meter reading drops for increased input voltage, but the drop is less and less rapid as voltage increases. This permits the same meter to be used for preliminary rough adjustments and the final balance.

The indications are received as deflections on a pen-type recorder.[5] The apparatus is adjusted so that the pen draws a line down the center of the paper chart. If a gun is brought through the doorway, the pen first swings in one direction, reaching a peak deflection when the gun is about 2 ft from the plane of the doorway. The deflection then reverses, swings across the center line as the gun passes the plane of the doorway, and reaches a reverse peak when the gun is about 2 ft beyond the doorway. There is some lag in pen response, but the operator may easily make allowance for it. A piece of nonmagnetic metal, if highly conductive like copper or silver, will show up with deflections opposite to those expected for iron, and much smaller for a given amount of metal.

In addition to the recorder, a sound alarm (not shown in circuit diagram) is provided.[5] The sound is a tone which is interrupted or continuous, depending on the strength of the indication. A small speaker in the control unit and two extension speakers carry this sound to the desired locations. Each speaker has a volume control. The speakers are turned on by three relays which may be set to trip at three desired values of the indication. The first relay, which trips on a small signal, puts the sound on with rapid interruptions. The second relay reduces the interruptions to a slow rate; and the third relay, which trips on the strongest deflection, makes the tone continuous. The relays stay closed until manually reset.

9.5 HISTORY

The method first tried[1] was to detect weapons by their magnetic effect. An attempt was made to develop an electrical apparatus which would be sensitive to the presence of very small variable magnetic fields but insensitive to the presence of the very much stronger fixed component of the earth's field at the pickup units.

Pickup coils designed to detect very small changes superimposed on the earth's field were to be arranged as shown in Figure 6. Coils marked *A-A*, *B-B*, etc., were to be connected in series opposition so that the effects of distant magnetic objects would cancel out, whereas the effect of a magnetic object nearby could not do so.

A general idea of the operating principle of

each detecting unit (i.e., each pair of coils in series opposition) can be obtained from the block diagram of Figure 7. Each pickup coil consists of a primary coil and a secondary coil.

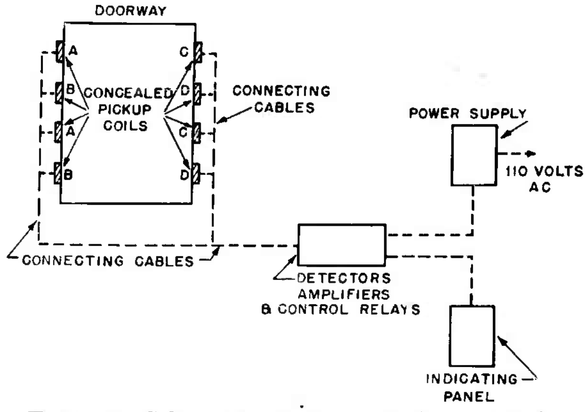


FIGURE 6. Schematic arrangement for magnetic detection method.

Pulses from the oscillator saturate the primary circuit of the pickup coils. The voltage developed in the secondary of the pickup coil depends critically on the component of magnetic field imposed parallel to the axis of the coil. The fundamental idea of the arrangement is that the presence of a metallic object will affect the voltage developed in the secondary circuit of the pickup coil. Energy from the secondary circuit is rectified at the diode detector and appears as a biasing voltage at the grid of the pentode amplifier. This voltage is the difference of the two voltages developed in the secondary coils, since the secondaries are in series opposition. The actual voltage developed at the diode is much less than the total voltage induced in each secondary coil. Any change in the external magnetic field around the pickup coils will cause a proportional change in the secondary-circuit voltage, thus producing more or less rectified voltage at the diode detector. This voltage is filtered and passed directly to the pentode amplifier.

Changes in plate voltage at the pentode amplifier are passed on to the phase-inverter stage, which divides the voltage changes into two channels. One channel produces an increase in voltage for an increase in voltage at the pentode amplifier plate; the other channel produces a decrease in voltage for an increase in voltage at the pentode amplifier plate. This method was chosen so that the control relays actuating the indicating apparatus could be of the simple nonpolarizing type. For any change in the magnetic field greater than a fixed minimum value at the pickup coils, one or the other of the relays will operate. Changes in plate voltage at the output of the phase-inverter stage are amplified by the buffer stage and passed on to the final power amplifier stage, which is capable of developing a sufficiently large current change in

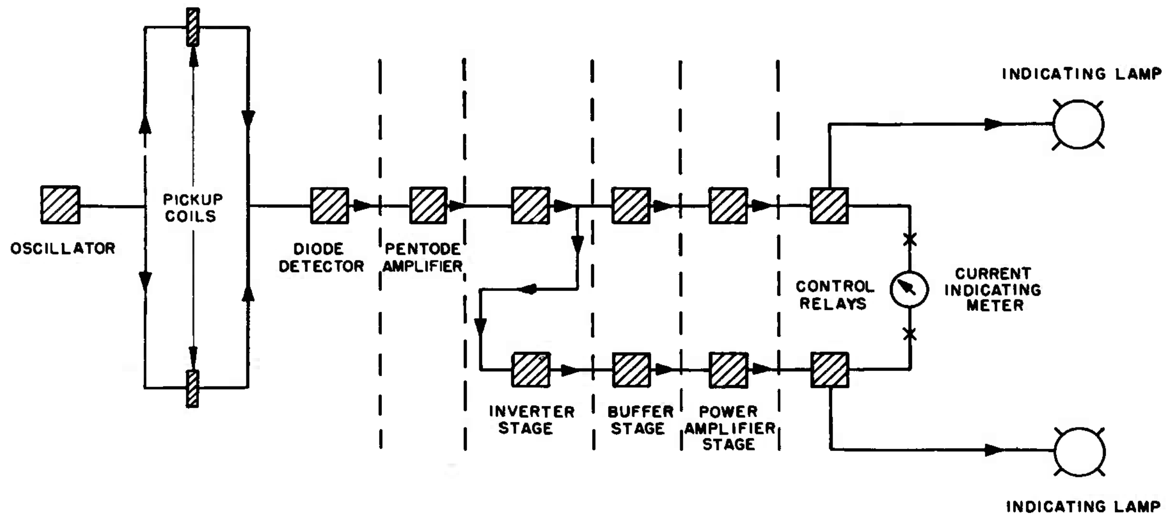


FIGURE 7. Block diagram for magnetic detection method.

its plate circuit to actuate the control relays. These relays operate the two indicating lamps, one for each channel. The current meter is in the common plate-supply circuit to the final amplifier stage, and shows an increase in current for a change of the magnetic field in either direction at the pickup coils.

Considerable work was expended on this method, but it offered so many difficulties in obtaining a sufficiently steady oscillator and in discrimination that it was ultimately abandoned. It was found that a gun could have a very weak magnetization of its own, just strong enough to be neutralized in certain positions by the earth's field. This occasionally resulted in zero indication. On the other hand, small objects such as mechanical pencils were too often found to be magnetized so highly that their effects were similar to that of an average gun.

Variations of the method were also considered, such as magnetization of all objects before attempted detection, demagnetization before attempted detection, and a system of magnetization and detection immediately followed by demagnetization and detection. All such magnetic methods were finally discarded in favor of the electromagnetic-field method.

Chapter 10

SURGEON'S METAL LOCATOR

10.1 INTRODUCTION AND SUMMARY

THIS PROJECT was undertaken with the hope of improving upon the locators already available. These locators are of the probe type and depend for their operation upon the change in coupling between two coils wound together upon the probe when a small ferrous object is brought near the probe. The coils are connected in a bridge circuit, and the degree of unbalance is indicated on a sensitive meter. The disadvantages of this type of instrument are the inconvenience of using a meter as an indicator, the lack of sensitivity to nonferrous objects, and the inability to indicate depth.

The locator, as finally developed, uses an audible signal as an indicator. When a metallic object is brought near the probe, the pitch of the audible signal is changed. The instrument depends for its operation upon the change in frequency of an r-f oscillator by eddy currents set up in a metallic object brought near the probe. This locator does not suffer from the first two difficulties mentioned above, but, like the other probe-type locators, cannot indicate depth. A caliper-type locator was developed which could be used to indicate depth. Since it depended upon the magnetic properties of the object it was insensitive to nonferrous objects. It also proved unstable and hard to balance, and was unsatisfactory except in the hands of a skilled operator. It was therefore decided to use a probe-type locator as a supplement to X-ray investigations. In use, the approximate position of the object is found by X-ray, the approximate surgical approach is made, and the locator used to guide further incision.

10.2 EXPERIMENTAL LOCATORS[1, 2]

Much of the development work done on locators was concerned with the caliper type in the hope that a workable instrument could be developed which would make possible the localization of the object in three dimensions, and thus remove the need for X-rays. The instrument developed used two primary coils as one side of an inductive bridge. The two secondary coils, which are on the two sides of the caliper (shown in Figure 1), are connected in parallel opposition. This arrangement was found empirically

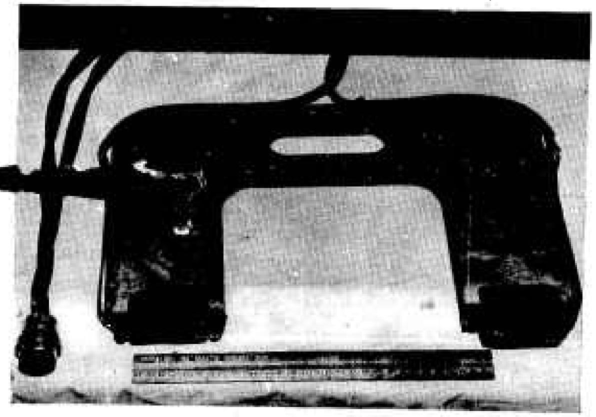


FIGURE 1. Caliper form of surgeon's metal locator.

to give the most stable and most sensitive locator. The instrument was first tried using 60-c current, but it was found that the 60-c pickup from the room rendered the locator very unstable. Accordingly, 30-c current was used in the coils, and a low-pass filter was put in the amplifier to remove the 60-c pickup. This large filter and the motor-generator set (which supplied the 30-c current) made the instrument quite bulky. The output of the bridge is amplified, rectified, and applied to the grid of a relaxation oscillator which produces an audible signal. The introduction of a ferrous object between the coils produces an unbalance of the bridge and a change in the audible signal, with the change being greatest when the object is directly between the coils. This locator proved capable of locating an object within a region about ½ in. in diameter. However, it was bulky, used quite a bit of power, and had a tendency to be unstable except in the hands of a skilled operator.

A similar arrangement was tried using an

r-f current instead of the l-f current. In this locator the two primary coils were connected in series and served as the tank coil of a 456-kc crystal-controlled oscillator. The particular frequency was chosen because of the ready availability of components. The two pickup coils were again connected in parallel opposition. This locator proved to be moderately sensitive and of equal sensitivity for nonferrous and ferrous materials. However, it proved quite unstable and had one insurmountable difficulty, namely, the absorption of power by the patient's body.

Other methods which were tried, but which were not so successful and were not developed further, include: a method in which the efficiency of a tuned transformer is changed by the proximity of a metallic object; a method in which the inductance is used in a phase-shifting circuit, a change in the plate current of a thyratron tube being caused by a change in the inductance; and an entirely different scheme in which a beam of X-rays passed through the body and was received on a fluorescent screen, the resulting light being measured by a photocell.

10.3 THE FINAL LOCATOR

The locator, as finally developed and manufactured, is shown in Figure 2. The exploring point of the probe consists of an oscillator coil, whose associated tube, choke, and condensers are contained in the handle of the probe. The frequency of operation of the system is approximately 5.5 mc. The control box contains another oscillator, whose frequency can be varied by the tuning control. Signals from the two oscillators are fed to the grids of a mixer tube, and the beat note produced is amplified and fed to the loud-speaker.

The locator is sensitive to metals by reason of their conducting properties. When a piece of conducting metal is brought into the r-f field of the probe oscillator, eddy currents are produced, and the frequency is increased. If the tuning control is set so that the frequency of the control-box oscillator is below that of the

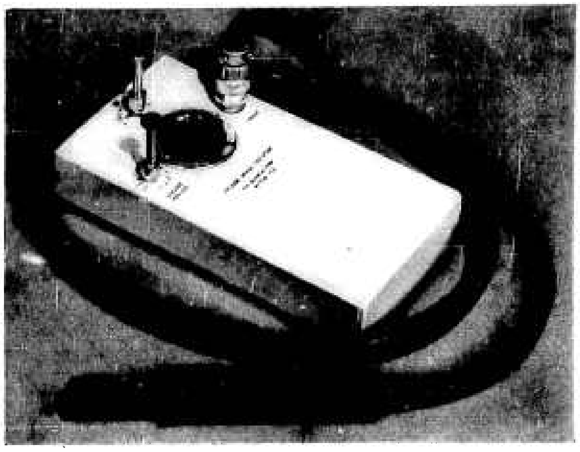


FIGURE 2. Final production model of surgeon's metal locator.

probe oscillator, the approach of the probe to a metallic object will produce a rise in frequency of the audible signal.

In the case of iron and steel, the effect of eddy currents in increasing the frequency is balanced to some extent by the increased inductance and decreased frequency caused by the magnetic permeability. An almost complete balance between the two effects is obtained on a piece about 1 mm in diameter and 1 cm long. A smaller magnetic needle causes a lowering of pitch. For pieces of iron larger than 3 mm in diameter, the effect is not noticeable, and these pieces can be found as readily as nonferrous metallic objects.

The locator is meant to be used in conjunction with X-rays, as described in the introduction, although it is frequently possible to locate an object from the surface. The large probe will indicate the presence of a .45-caliber lead bullet at a distance of 1½ in. or a .22-caliber short lead bullet at ⅞ in.

GLOSSARY

α-RAY. A doubly ionized helium atom.

ANTI-PERSONNEL MINE. A low-pressure-functioning mine (perhaps 5 lb) with a small explosive charge (e.g., 200 g TNT) capable of being actuated by a man's weight.

ANTI-TANK MINE. A mine containing an explosive charge sufficient to disable a tracked vehicle (a charge of, say, 10 lb of TNT) and usually requiring several hundred pounds force to actuate. Some anti-tank mines, such as the Japanese Type 3 Flower Pot, are both anti-personnel and anti-tank since they are actuated by a few pounds' weight.

GAMMA. 1 gamma is 10^{-5} oersted.

γ-RAY. A high-frequency electromagnetic wave pulse emitted by radioactive atoms.

GEIGER-MUELLER COUNTER. A gas-filled tube by which γ-rays and other rays are detected by means of a cascade ionization process.

JANET BOARD. Joint Army and Navy Experimental and Testing Board.

METALLIC MINE. A mine containing sufficient metal parts (perhaps only a spring) to be detectable by a mutual inductance-type mine detector.

NONMETALLIC MINE. A land mine fabricated entirely of nonmetallic components.

RU. Receiver unit.

TU. Transmitter unit.

VHG. Vertical-horizontal gradiometer.

VVG. Vertical-vertical gradiometer.

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CONTRACT NUMBERS, CONTRACTORS, AND SUBJECT OF CONTRACTS

The contract information given below is for Division 17 work reported in (or related to) this volume. Contract information associated with Division 17 work reported in other volumes of the Division 17 Summary Technical Report is given in those volumes.

The work under contracts whose numbers are marked with an asterisk (*) is not discussed anywhere in the Division 17 STR. For details of such work the reader is referred to the NDRC Bi-Monthly Summaries. The contracts themselves are listed here for completeness of contract information.

Contract Number	*Name and Address of Contractor*	*Subject*
NDCrc-64*	Princeton University Princeton, New Jersey	Studies and experimental investigations in connection with Submarine Mines.
NDCrc-81	The Union Switch and Signal Company Swissvale, Pennsylvania	Studies and experimental investigations in connection with circuits used to operate submarine mines at the Submarine Mine Depot, Fort Monroe, Virginia.
NDCrc-99	Gulf Research and Development Company Pittsburgh, Pennsylvania	Studies and experimental investigations in connection with the development of a magnetic detector responsive to changes in magnetic fields and designed to indicate the approach of ferromagnetic objects.
NDCrc-111	The Johns Hopkins University Baltimore, Maryland	Studies and experimental investigations in connection with the development of an instrument for detecting and measuring small concentrations of noxious gases in the atmosphere with particular regard to building an instrument which is portable, simple to operate, and reliable.
NDCrc-158*	Drexel Institute Philadelphia, Pennsylvania	To perform consultation and investigational work in connection with the studies of the behavior of submarine mines when subject to tidal and wave action and the shock wave of an exploding neighboring mine.
NDCrc-187	Carnegie Institution of Washington Washington, D. C.	Studies and experimental investigations in connection with (1) problems, such as those of magnetic compensation, and of optimum location, arising in conjunction with the use of magnetic compasses in tanks and other vehicles; (2) similar problems which may arise in conjunction with the use of magnetic compasses in Naval craft; (3) continued consultation, tests, and redesign of vehicular odographs, marine odographs, and aircraft odographs, pedographs, and dead reckoning tracers generally; (4) the development of a

Contract Number	*Name and Address of Contractor*	*Subject*
		detonating mechanism for use with explosive charges, which mechanism is to be actuated by the magnetic field of a tank or other vehicle; (5) the study of the magnetic characteristics of vehicles, or Naval craft, when necessary in connection with (1), (2), (3) and (4) hereof; (6) the development of a detector for magnetic masses, such detector to be free of any substantial external field of its own; and (7) such other related problems as may arise from time to time.
NDCrc-199*	Massachusetts Institute of Technology Cambridge, Massachusetts	Studies and experimental investigations in connection with the development of suitable apparatus for the measurement of stresses and strains produced in submerged metallic objects by underwater explosions.
OEMsr-47	Massachusetts Institute of Technology Cambridge, Massachusetts	Studies and experimental investigations in connection with the development of a device for arming controlled submarine mines by means of acoustic waves emitted by an approaching vessel.
OEMsr-95	Gulf Research and Development Company Pittsburgh, Pennsylvania	Studies and experimental investigations in connection with the development of an improved magnetic device for use of magnetic land mines.
OEMsr-150	Hazeltine Service Corporation New York, New York	To conduct . . . studies and experimental investigations in connection with anti-tank mine locators, to investigate all likely methods, apparatus, and circuits adaptable for use in locating metallic anti-tank mines, to investigate the application of any device developed in connection therewith to possible nonmetallic mines having a small metallic fuse bo· . . . and to deliver working models of any devices developed hereunder.
OEMsr-151	Carnegie Institution of Washington Washington, D. C.	Studies and experimental investigations in connection with (i) the magnetic field at various depths beneath and around tanks and motorized vehicles, (ii) the effects of deperming and degaussing on these magnetic fields, (iii) the most suitable location for degaussing coils on motorized vehicles from practical and theoretical points of view, (iv) the development of a mechanism operated by the magnetic fields of vehicles suitable for the discharge of land mines to test the effectiveness of protection, and (v) the development of a method of detecting land mines in ferromagnetic cases, particularly such methods as may be employed in connection with the operation of motorized units.

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-178	The Johns Hopkins University Baltimore, Maryland	Studies and experimental investigations in connection with (i) methods of infrared detection of gases and the development of apparatus for detecting CO, CO_2, and H_2 in submarines, together with additional equipment for detection of toxic gases, and the increase of the sensitivity of the instruments developed hereunder, (ii) the construction of up to five (5) of each of two (2) kinds of instruments, one a selective gas detector, and the other a non-selective detector, (iii) the modification of the design of the infrared gas detector to give shorter reaction time and to provide air cooling, and the construction of at least one (1) model thereof, and (iv) the design of an instrument suitable for the measurement of small concentrations of water vapor.
OEMsr-266	Gulf Research and Development Company Pittsburgh, Pennsylvania	Studies and experimental investigations in connection with the development of (i) improved methods of submarine mine control, (ii) a security device, (iii) an improved helium purity indicator for use in range-finders and lighter-than-aircraft, (iv) a device for the determination of the quantity of fuel in the tanks of aircraft, (v) an indicator mine and associated devices and methods for determining the effectiveness of various explosive means of clearing minefields, and (vi) other instruments and devices of warfare when and as requested in writing by the Contracting Officer or an authorized representative.
OEMsr-295	Massachusetts Institute of Technology Cambridge, Massachusetts	Studies and experimental investigations in connection with the development of a detector of approaching vessels which will operate from the reflection of a sound wave which has been emitted by an anchored submarine mine, and which is received back within a time interval corresponding to the danger range of that mine.
OEMsr-328	The Union Switch and Signal Company Swissvale, Pennsylvania	Studies and experimental investigations looking toward the development of a pilot model of a circuit for controlling harbor mines based on a frequency selection method capable of operating two (2) sets of thirteen (13) mines from a single control panel, and such further studies on control circuits for influence mines as may be requested by the Contracting Officer or his authorized representative.
OEMsr-419	The Regents of the University of Wisconsin Madison, Wisconsin	Studies and experimental investigations in connection with the development, in cooperation with approved electronics engineers, of an improved instrument for locating metal fragments imbedded in human tissue.

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-667	Brown University Providence, Rhode Island	To conduct studies and experimental investigations in connection with the improvement of existing sound ranging systems and more particularly, to estimate impartially their capabilities, offer suggestions for their improvement, and indicate the direction to be taken by fundamental development work.
OEMsr-734	Duke University Durham, North Carolina	To conduct . . . studies and experimental investigations in connection with the problem of ranging enemy guns by sound and, more particularly, to (i) study and develop gun ranging and locating systems; (ii) collect phonographic and oscillographic records of the sounds of gun fire, the ballistic noise of projectile and other battle noises; and (iii) develop apparatus for gun ranging systems.
OEMsr-749	Kannenstine Laboratories Houston, Texas	Studies and experimental investigations in connection with the development of devices and methods for locating unexploded bombs, in cooperation with the Bomb Disposal School, Aberdeen Proving Ground, Aberdeen, Maryland.
OEMsr-958	S. A. Scherbatskoy Tulsa, Oklahoma	Conduct studies and experimental investigations in connection with and construct models of devices to locate nonmetallic mines by neutron and seismic methods.
OEMsr-998	Sun Oil Company Philadelphia, Pennsylvania	Studies and experimental investigations in connection with the use of high frequency electric currents for the purpose of locating concealed metallic and nonmetallic objects.
OEMsr-1035	Leeds & Northrup Company Philadelphia, Pennsylvania	Studies and experimental investigations in connection with (i) the engineering, design, development, and construction of five (5) pilot units of a gas analyzer, (ii) the means for improving the design of the filter cones, methods of standardizing such units, and to cooperate in the study of and application to various problems for which this instrument is suited, (iii) the redesign of the gas analysis instrument to increase the sensitivity by including vacuum thermopiles and energy sources, and the construction of five (5) pilot models of the redesigned instrument, and (iv) the investigation of such other means of improvement as may be mutually agreed upon between the Contractor and the Scientific Officer.
OEMsr-1042	The Maico Company, Incorporated Minneapolis, Minnesota	Conduct (i) studies and experimental investigations in connection with and produce ten (10) models of the Gilson type of Surgeon's Metal Locator, including such circuit and other redesign as may be agreed upon, and (ii) field trials thereof.

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-1061	Radio Corporation of America RCA Victor Division, Camden, New Jersey	Studies and experimental investigations in connection with (i) certain acoustic and electric methods of locating land mines, particularly nonmetallic units, (ii) the construction of one or more models of any apparatus developed, and (iii) the construction of seven (7) additional units of the improved UHF nonmetallic mine detector.
OEMsr-1063	Electro-Mechanical Research, Incorporated Houston, Texas	Studies and experimental investigations in connection with (i) potential drop ratio methods of locating land mines, (ii) alternating current inductive methods, particularly in the frequency range of 100 to 500 kc, and (iii) redesign for production the prototype model of the induced earth current detector developed hereunder.
OEMsr-1076	Marmon-Herrington Company Indianapolis, Indiana	Studies and experimental investigations in connection with the development of mechanical means for the clearing of anti-tank mine fields.
OEMsr-1114	The Texas Company Houston, Texas	Studies and experimental investigations in connection with the development of a detector for anti-tank mines by means of the masking effect of the mine on the natural radio-activity of the earth.
OEMsr-1156	Massachusetts Institute of Technology Cambridge, Massachusetts	Studies and experimental investigations in connection with possible methods of locating enemy mines by means of devices using sources of neutrons and detectors for the reflected or scattered neutrons including the design of such special detectors.
OEMsr-1234	Carnegie Institute of Technology Pittsburgh, Pennsylvania	(i) Conduct studies and model experiments in connection with establishing fundamental data required for improving the design of flailtype mine exploders and (ii) make a preliminary investigation of a sound pressure type of fuel quantity gage, particularly for aircraft.
OEMsr-1374	Polytechnic Institute of Brooklyn Brooklyn, New York	Studies and experimental investigations in connection with the various aspects of the propagation of UHF radiation in soil, and the development of devices for the purpose of detecting land mines based on such investigations.
OEMsr-1401	The Burdick Corporation Milton, Wisconsin	Construct ten units of the Gilson portable metal locator.
OEMsr-1463	Shell Oil Company, Incorporated Houston, Texas	Studies and experimental investigations in connection with the methods of detecting all types of mines by means of currents introduced into the ground other than those currents induced by the detecting device itself.

CONTRACT NUMBERS, CONTRACTORS, AND SUBJECT OF CONTRACTS (*Continued*)

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-1470	The Elflex Company Houston, Texas	Studies and experimental investigations in connection with methods of detecting all types of mines by means of currents introduced into the ground other than those currents induced by the detecting device itself.
OEMsr-1489	Massachusetts Institute of Technology Cambridge, Massachusetts	Studies and experimental investigations in connection with the development of means for locating fragments of methyl methacrylate or similar materials when embedded in the human body.

SERVICE PROJECT NUMBERS

The projects listed below were transmitted to the Executive Secretary, NDRC, from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department. Service Projects marked with an asterisk (*) are not discussed anywhere in the Division 17 STR. For details of such work the reader is referred to the NDRC Bi-Monthly Summaries.

Service Project Number	*Subject*
	Army Projects
AC-123	Development of instrument for detecting methyl methacrylate particles in the human body.
CAC-1	An influence operated mine for defense against submarines (later OD-69).
CAC-4*	Natural phenomena forces recorder.
CAC-5*	Explosive-wave phenomena recorder (mine explosions) (later OD-70).
CAC-7	Frequency selection system for controlled submarine mine (later OD-72).
CE-4	Anti-tank detection device.
CE-31	Development of a method of detecting explosives.
CE-31 Ext.	Development of a combined metallic and nonmetallic mine detector.
CE-31 Ext.	Portable underwater mine detector.
CE-32	Minefield clearing devices.
CE-32 Amend.	Assistance of NDRC on blast research problems.
CE-32 Ext.	Design of an electrical circuit for firing a projected line charge developed for clearing paths through mine fields.
OD-46	Development of methods for the protection of tanks against anti-tank land mines and techniques for testing these methods.
OD-63	Bomb disposal technical assistance.
OD-69	Influence operated controlled submarine mine (formerly CAC-1).
OD-70*	Explosive-wave phenomena recorder (mine explosions) (formerly CAC-5).
OD-72	Frequency selection system for controlled submarine mine (formerly CAC-7).
OD-133	The study of the design of flails.
OD-134	Self-propelled mine clearing devices.
SOS-13	Gun ranging.
	Navy Projects
MC-100	Sound ranging equipment for the Marine Corps.
MC-100 Ext.	Procurement of dodars; 100 acoustic coupler tubes, to adapt the T-21-B microphones to dodar use.

INDEX

The subject indexes of all STR volumes are combined in a master index printed in a separate volume. For access to the index volume consult the Army or Navy Agency listed on the reverse of the half-title page.